Prescriptions for optimal management of stony soils at Te Whenua Hou in Canterbury, New Zealand

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Abstract

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Te Whenua Hou (Eyrewell forest) is a Ngāi Tahu plantation forestry-to-dairy conversion which also has ecological values related to a threatened and residual native flora and fauna. Eyrewell soil is typified by its high stoniness with high drought vulnerability and potential high susceptibility to rapid leaching of water and nutrients. An abundance of rock fragments provides a restrictive water storage capacity. These factors raise a number of environmental concerns, both for transfer of nitrates to the wider environment and for the estabilishment of vegetation. Mediation of these concerns clearly would be of value both to agriculture and to restoration. The present study aims to provide an optimal prescription for stony soil management in Eyrewell to achieve successful land use outcomes.

The present research project includes an investigation of current soil status at Te Whenua Hou, laboratory-, greenhouse-, and lysimeter-scale trials, and field research. Eyrewell soil has not been properly investigated since the land conversion, so the physical condition of current Eyrewell soil was identified by excavating soil profiles. Then, water flow patterns were observed by visualizing flow paths using a dye tracer. In the laboratory, the effects of rock fragment content and sizes on water flow rates were studied within repacked soil columns. The combined effect of rock fragments and living plant roots on nutrient leaching was investigated in a greenhouse pot trial. In addition, the effect of rock fragments on solute transport was explored using established lysimeters which had formerly supported crops and were likely to have contained decayed root channels. Lastly, a field investigation was conducted on the relationship between rock fragment content, properties of adjacent soils, and tension infiltration rates.

The results revealed that rock fragments have a complicated effect on water flow and solute transport depending on rock fragment content and their contribution to continuous pore space. Intermediate rock fragment content reduced water flow rates, but high rock fragment content

induced rapid and intensive leaching by reducing the water-holding capacity of soils and creating large voids. Living plant roots could reduce the nutrient leaching in stony soil, but dead or decayed root channels became the main pathways of preferential flow, which enhanced nutrient leaching. Intermediate rock fragment content contributed to decreasing nutrient leaching through those root channels by increasing the tortuosity of the channels. However, high rock fragment content created additional preferential flow pathways and increased solute transport.

The findings of this research project show that the effects of changing rock fragment content are often couter-intuitive. Furthermore, there are substantial differences in hydrology between repacked soil columns and in-situ field studies. Laboratory studies must be extrapolated with care. Integration of the findings of this research project led to a commendation to remove 6-10 % of rock fragments from 0-40 cm depth, and 26-30 % of rock fragments from 40-80 cm depth. This removal would be likely to reduce up to 25 % of water leaching and 21 % of nutrient leaching.

Keywords: Eyrewell, rock fragments, stony soil, preferential flow, saturated hydraulic conductivity, tension infiltration rates, solute breakthrough curves, plant root channels, in-situ soil water flow

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Chapter 1

Introduction

1.1 General introduction

1.1.1 Background

The Canterbury plain has various geographical and meteorological features such as volcanoes, rivers, sand dunes near the coast, and strong winds with a wide range of unique flora and fauna adapted to these conditions (Williams, 2005). However, natural habitats in the Canterbury plains have been changed dramatically in the last 800 years. The first anthropogenic disturbance in this area was through Maori fires, which destroyed most of the native forest on the plains, after which kānuka shrubland (*Kunzea serotina*, Myrtaceae) became the dominant vegetation cover. After European settlement, the kānuka and associated tussock grasslands were replaced by pasture to create sheep farms. In the early 1900s, when New Zealand was in economic depression, unemployed workers were employed to plant exotic pine tree forestry plantations in the Eyrewell region (Wendelken, 1966). Eyrewell is located on the north bank of Waimakariri River, north-west of Christchurch (Figure 1.1). Ownership of this land was returned to Maori in 2000 and the forestry license was expired, after which the forest has been converted into a dairy farm landscape. Conversion processes involved removing root boles and forestry trash using root rakes, stick rakes, and buck rakes. Bulldozers and diggers were used for land clearing, and tractors with stick rakes and buck rakes with loaders were used for a final stick picking. Before sowing grass seeds, traditional cultivation techniques were applied including discing and levelling with two passes. A final pass was carried out with high-speed discs and harrows before drilling grass seed in the soil using a roller. Rock fragments were not removed from the soil, but of course the location of each rock fragment would have been altered. Five years later, Eyrewell was mostly dairy pastureland with some remaining forest with exotic species (Ecroyd & Brockerhoff, 2005). More recently, 17 reserve areas covering >150 ha have been set aside for restoration planting, with a similar amount of native planting on farm and paddock borders, under irrigators alongside roadways, and around farm buildings (Dollery, 2016; "Ngāi Tahu Farming", n.d.). Through this type of land conversion, the wider Canterbury plain has lost much of its native flora and fauna, and has become one of the most depleted areas for native biodiversity in New Zealand (Winterbourne et al., 2008). Despite this, 25 % of New Zealand endangered native plants and 15 % of endangered wild animals are still living in the region (Williams, 2005).

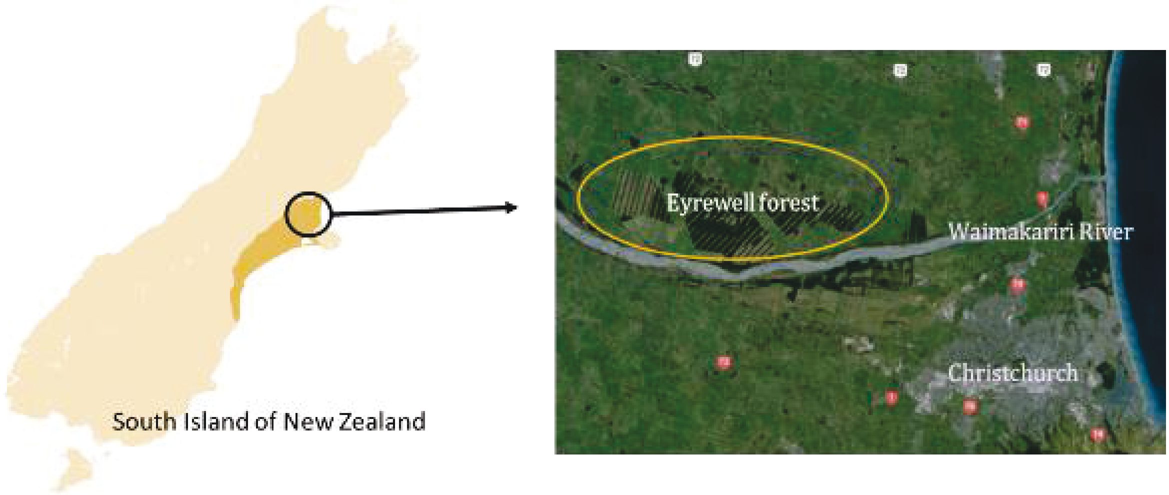

Figure 1.1. Location of the Canterbury plain and the Eyrewell forest.

1.1.2 Research gap

The physical chemical properties of Eyrewell soil is one of the challenges for agricultural development and also an obstacle to the restoration project (Dollery, 2017). Eyrewell soil contains a lot of stones and gravel (Figure 1.2). These soils are well-drained with high drought vulnerability. At the same time, ponding of water occurs on the surface in places (Figure 1.3), which may have been induced by soil hydrophobicity and compaction of the soil surface. Free-draining soils increase the nitrate concentration in groundwater by transporting water and nutrients faster (Nolan & Stoner, 2000); clearly, this creates environmental concerns. A prescription to alleviate nutrient leaching would be highly desirable, but there have been only a few previous studies on Eyrewell stony soils. An optimal soil prescription is important because it is likely to be closely related to water flow and storage (Pachepsky & Rawls, 2003). A better understanding the Eyrewell soil is important for the successful management in this landscape.

Figure 1.2. Eyrewell soil contains a significant portion of stones and gravels.

Figure 1.3. Ponding water occurs on the surface soil in places at Eyrewell.

1.2 Aims and objectives

This research aims to investigate optimal prescriptions for stony soil management in the agricultural and restoration landscapes of Eyrewell forest. This research is composed of laboratory, grasshouse, and field experiments on the effect of rock fragments on soil water flows, and the combined effect of rock fragments and plant root systems on the soil water flow and solute transport. The field investigation seeks to identify the current physical and hydrological status of Eyrewell soil.

The PhD research programme had the following objectives:

Objective 1: To visualize water flow patterns related to soil characteristics in-situ at Eyrewell (Chapter 3).

Objective 2: To identify the effect of rock fragment content and size on soil hydraulic properties in repacked soil columns (Chapter 4).

Objective 3: To study the effect of rock fragments and plant roots on nutrient leaching in pot-scale experiments (Chapter 5).

Objective 4: To investigate the effect of rock fragment content and decayed plant root channels on solute transport in a lysimeter-scale experiment (Chapter 6).

Objective 5: To evaluate the overall effect of rock fragments on other soil properties and in-situ water flow in Eyrewell soil (Chapter 7)

1.3 Chapter description

Chapter 2: Literature review

This chapter provides a detailed literature review. Firstly, the environment of Eyrewell including the climate and soil properties is described. Secondly, a rock fragment classification and general methods for a stony soil investigation are reviewed. Then, the impact of the rock fragment on soil physical and chemical properties, surface and subsoil hydrology, and the plant growth are reviewed.

Chapter 3: A field study on the current water flow patterns in Eyrewell

This chapter addresses Objective 1. This objective was demonstrated in the field. A dye tracer was applied into the Eyrewell soils, and then, the stained water flow patterns were observed after soil excavation. Dye flow patterns with the existence of rock fragments were compared. The soils next to the dye application plot were collected, and their physical and chemical characteristics were analysed. The visualized water flow patterns are discussed related to soil characteristics.

Chapter 4: Effect of rock fragment contents and sizes on soil hydraulic properties in repacked soil columns

This chapter addresses Objective 2, investigated through laboratory trials. Small columns were packed manually with various quantity and mixed sized of rock fragments. Saturated hydraulic conductivities and tension infiltration rates were measured, and then, the effects of rock fragment contents and sizes on these hydraulic properties are discussed.

Chapter 5: Sole and combined effect of rock fragments and plant roots on soil water flow and nutrient leaching

This chapter addresses Objective 3. This objective was demonstrated using greenhouse trials. Ryegrass and maize were grown in repacked 0 % and 25 % stony soils in the greenhouse. Plant growth, the volume of leachate, solute breakthrough curves, and the amounts of nutrient leaching are compared. The sole and combined effect of rock fragments and plant roots on soil water flow and nitrate leaching are studied.

Chapter 6: Effect of rock fragment content and decayed root channels on solute transport in an unsaturated lysimeter system

This chapter addresses Objective 4. This objective is a collaboration work with Plant and Food Research (A New Zealand Crown Research Institute). They provide a lysimeter system including TDR recording of soil moisture and electrical conductivity and leachate collection. The lysimeters had been packed with 0%, 30%, and 50% rock fragments. Different kinds of crops had been grown in the lysimeters over two previous growth seasons, so longer-term complex decayed root networks existed in each lysimeter. Solute movement tests by applying bromide tracer were conducted, and the effect of rock fragments and decayed plant roots on the solute transport are discussed.

Chapter 7: Effect of rock fragments on in-situ soil water flow in Eyrewell

This chapter addresses Objective 5. This objective questioned how the rock fragments influence the other soil properties, and how they have a combined impact on soil water flow in a field. To investigate these questions, tension infiltration tests with four different tensions were carried out in a farm margin area in Eyrewell. The soils beneath the infiltrometer were collected and their physical and chemical properties were analysed. The relationship between rock fragment content and soil properties were analysed, and the effect of rock fragments on in-situ water flow is discussed.

Chapter 8: Conclusion

This chapter re-visits each objective, providing overall conclusions, and the applications and contributions of this research to knowledge, with recommendations for further research.

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Chapter 2
Literature review

2.1 Stony soils in the world

Rock fragments are commonly found in many soils as a consequence of natural processes or human activities (Zhang et al., 2016). Soils containing a large number of rock fragments are widespread around the world comprising 30 % of soils in Western Europe, 60 % in the Mediterranean area, and 18 % of mountain soils in China (Ma & Shao, 2008; Poesen & Lavee, 1994). In addition, soils containing rock fragments represent a significant part of arable lands (Miller & Guthrie, 1984), and are a component of this important resource for human beings (Ma & Shao, 2008). In spite of the significance of rock fragments, research experiments tend to remove or ignore them in soil studies (Torri et al., 1994). There is now an increased interest to identify the relationship between rock fragments and soil properties, such as bulk density, water and nutrient dynamics, and porosity (Poesen & Lavee, 1994; Qin et al., 2015; Rücknagel et al., 2013; Rytter, 2012), although the study of the rock fragments is still scarce (Beckers et al., 2016).

2.2 Eyrewell environment

2.2.1 Climate

The Canterbury Plain has an average annual precipitation around 600 mm (Macara, 2016), which is approximately less than half of that in Auckland and Wellington. Rainfall events vary seasonally and between years. Mean temperature is lowest in July (5 ℃) and highest in January (17 ℃). From October to February, humidity is very low, so evaporation rates are high (Wendelken, 1966). During this period, evaporation can exceed precipitation for up to six weeks. Strong wind is one of the distinctive features in Eyrewell. The prevailing wind blows from the north-west and wind speed commonly reaches up to 90 km h^{-1}. Most of Eyrewell is very flat, but North-west Eyrewell, beyone the site of the present study, contains mountains and foothills which form valleys and gorges. The site of the present study is entirely flat, but these geographical features contribute to local turbulence and increase the power of the wind (Wendelken 1966).

2.2.2 The feature of Eyrewell soil

Te Whenua Hou (Eyrewell forest) is a 7000 ha gravel plain at an altitude of 215 m above sea-level. Eyrewell soil is silty-loams of alluvial origin; 65% is classified as Lismore and 35% as Balmoral soil.

Lismore soil, commonly found across Canterbury, has formed from gravely glacial outwash (Molloy, 1988). This soil contains a high proportion of rock fragments and a small amount of mineral soil (Di et al., 2007). The parent materials of the Lismore soil are greywacke gravels with a thin cover of loess, thus, the nutrient status of the Lismore is naturally very low (New Zealand Soil Bureau, 1968). Balmoral soil is also developed from North Canterbury and has a similar formation process and characteristics (Molloy, 1988). However, Balmoral soil was reported to have a higher potassium fixation and faster drainge than Lismore soil (Wheeler, 2016).

Eyrewell has four types of soil profile: a silt loam, a shallow silt loam, a stony silt loam, and a very stony silt loam (Molloy & Ives, 1972). The soil generally contains a great number of stones and gravels in various sizes. Mean rock fragment content is over 65% by weight in the top 80 cm of soils (Wendelken, 1966), but the content varies regionally (Wendelken, 1955). An intensive gravel layer is commonly found in soils, but the depth of the gravel layer is not constant (Riddell, 1979). The chemical characteristics of Eyrewell forest soil are summarized in Table 2.1. Eyrewell soil is of low productivity as it contains a low level of nutrients. Drought is another limiting factor for plant growth in this soil (Molloy & Ives, 1972). Soil moisture of Eyrewell soil does not satisfy the needs of agricultural plants. Precipitation is low and soils cannot maintain water efficiently. After rainfall events, water often ponds on the soil surface or stays in topsoils without percolating into deep soils (Wendelken, 1955). Thus, Eyrewell soil looses much of its infiltrated water by evaporation and transpiration (Wendelken, 1955).

Table 2.1. Chemical properties of Eyrewell forest soils (Kim et al., 2015)

pH	OM (%)	Total N (%)	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	Total P (mg kg^{-1})	Olsen P (mg kg^{-1})
5.0	4.3	0.1	0.2	<0.1	335	4.8

Eyrewell soil is known to present major constraints for plant root growth. Due to high stoniness, it does not allow deep root penetration. According to Wendelken (1955), root penetration in Eyrewell was limited less than 45 cm because subsoils were considerably compacted. Also, he found when plant roots encountered rock fragments during downward penetration, the roots changed in the direction of growth upward. The original downward growth of the roots left many hollows and cavities in the Eyrewell soil. When downward root growth was prevented, the roots became thinner, club-shaped, and distorted. Consequently, the trees in this area were unstable and sensitive to wind blow, which constrained the success of forestry production.

2.2.3 Recent studies in Eyrewell

Table 2.2 shows the studies which have been conducted in Eyrewell since 2000 which was when Maori recovered ownership of this land and a forest license was expired. The pine forest was converted to a dairy farm and, thus, soils were seriously disturbed. However, there has been little attention to the physical or chemical status of Eyrewell soil since the conversion. Most studies were related to the ecology or biology of the pine forest. Only a few studies, such as phosphorus leaching (Toor et al., 2004) and soil resistance and stability (Wakelin et al., 2014), were carried out with Eyrewell soil, which suggests that research on soil in this converted landscape would be worthwhile.

Table 2.2. Studies in Eyrewell since 2000.

Author	Subject
Moore (2000)	Differences in maximum resistive bending moments of *Pinus radiata*
Brockerhoff et al. (2003)	Diversity and succession of vascular plants in *Pinus radiata* plantation forests
Girisha et al. (2003)	Decomposition and nutrient dynamics of fallen pine needles
Ganjegunte et al. (2004)	Decomposition and nutrient dynamics of pine woody debris
Toor et al., (2004)	Assessment of phosphorus leaching from a free-draining grassland
Brockerhoff et al. (2005)	Role of pine forests in the conservation of endangered ground beetle *Horcaspis brevicula*
Ecroyd & Brockerhoff (2005)	Floristic changes over 30 years in a Canterbury Plains kanuka forest
Reay et al. (2008)	Isolation of fungi related to bark beetles in *Pinus radiata* plantation
Reay et al. (2010)	Isolation and characterization of fungi from *Pinus radiata*
Dungey et al. (2011)	Alternatives to *Pinus radiata* in terms of early growth
Wakelin et al., (2014)	Soil functional resistance and stability
Kim et al. (2015)	Interaction of native earthworms with soils and plant rhizosphere
Kim et al. (2017)	Molecular identification and distribution of native and exotic earthworms

2.3 Investigation of soils containing rock fragments

2.3.1 Definition of rock fragments

Rock fragments in soils have a huge influence on soil hydraulic characteristics, such as infiltration and water content (Miller & Guthrie, 1984). The term 'rock fragment' has been defined as soil particles larger than 2 mm in diameter (Miller & Guthrie, 1984). 'Rock fragment' has been used in preference to 'stone' because 'stone' refers to a particular size of rock fragments in various classification systems (Poesen & Lavee, 1994). Soil particles are divided into two main groups based on diameters; mineral soils (less than 2 mm) and rock fragments (larger than 2 mm) (Novák et al., 2011). Rock fragments are coarse inorganic fractions which occupy a considerable volume in a soil (Rytter, 2012). Table 2.3 shows different rock fragment classifications defined by various institutions and countries (Poesen & Lavee, 1994).

Table 2.3. Various rock fragment classifications defined by different institutions or countries (Poesen & Lavee, 1994).

Institution	Size (mm)	Classification
FAO	2-76	Gravel
	76-250	Stone
	Over 250	Boulder
U.K	2-6	Very small stone
	6-20	Small stone
	20-60	Medium stone
	60-200	Large stone
	200-600	Very large stone
	Over 600	Boulder
New Zealand	2-60	Gravel
	60-200	Cobble
	Over 200	Boulder
U.S.A. (rounded, angular or irregular rock fragments)	2-5	Fine gravel (pebble)
	5-20	Medium gravel (pebble)
	20-76	Coarse gravel (pebble)
	76-250	Cobble
	250-600	Stone
	Over 600	Boulder
U.S.A. (flat rock fragments)	0-15	Channer
	15-38	Flagstone
	38-600	Stone
	Over 600	Boulder

2.3.2 Techniques to evaluate a hydrological processes in stony soils

Field dye application

A dye application method has been widely used to investigate qualitative evidence in the studies of soil morphology, cracks and fissures, preferential flows, and solute transports (Zhang et al., 2016). Flury and Flühler (1994b) used this technique to compare soil water flows in structured and non-structured soils and the effect of irrigation methods on occurring preferential flows. Alaoui and Goetz (2008) investigated the influence of soil compaction and tillage on the macropore pathways by tracing a dye tracer. Laine-Kaulio et al. (2015) used the dye tracing method to identified water flow mechanisms of hillslope area.

To observe dye stains, the soil in which a dye tracer applied needs to be excavated either vertically or horizontally. A subsoil process of water flow can be observed by vertical excavation. The concentration of dye flow allows to quantifying infiltrated solutes (Weiler & Flühler, 2004) and the downward movement of contaminants (Cey et al., 2009). On the other hand, horizontal excavation enables to see the round distribution of dye stains spreading from macropores in the middle to the surrounding soils (Weiler & Flühler, 2004). From this observation, a macropore-matrix interaction between water and solute transports can be assessed (Cey et al., 2009). Exposed soil profiles can be photographed and digitalized for a quantitative study. There is no typical way of digital image processing, so scientists have been using various methods and software (Alaoui & Goetz, 2008; Flury & Flühler, 1994b; Laine-Kaulio et al., 2015; Wang & Zhang, 2017; Weiler & Flühler, 2004). Examples are shown in Table 2.4.

General parameters which can be observed from excavated soil profiles are the maximum depth of dye infiltration and dye coverage (Alaoui & Goetz, 2008; Flury & Flühler, 1994b; Laine-Kaulio et al., 2015; Wang & Zhang, 2017; Weiler & Flühler, 2004). However, Weiler and Flühler (2004) insisted that these basic parameters were insufficient to explain soil water movement, so they suggested a new method which classifies a water flow regime from dye flow patterns. Their proposed five water flow types are presented in Table 2.5.

Table 2.4. Digitally processed images of vertical profiles following dye application, using different software.

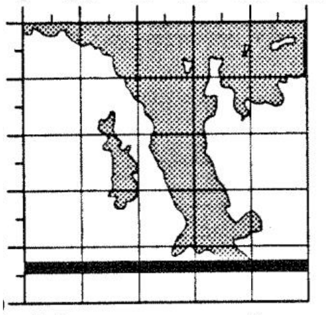
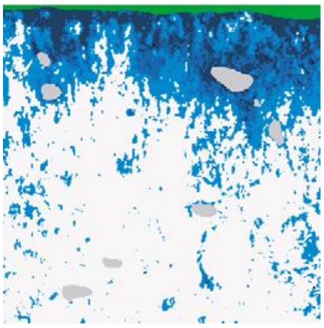
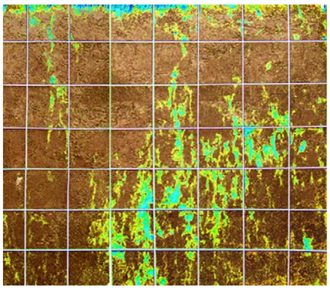
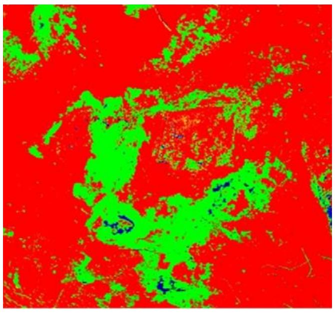
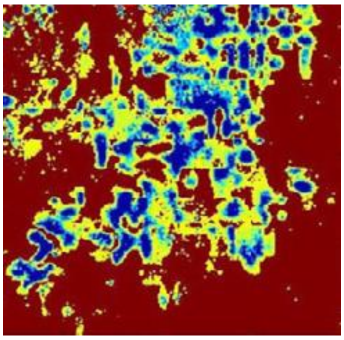
Softwater	Processed image	Authors
Summagraphics BitPad graphics tablet connected to an Apple Macintosh computer		Flury & Flühler (1994b)
IDL package		Weiler & Flühler (2004)
Photoshop CS2		Alaoui & Goetz (2008)
Gimp 2.8		Laine-Kaulio et al. (2015)
Photoshop 7.0 and ImageJ		Wang & Zhang (2017)

Table 2.5. Five flow types recognized by dye patterns (Weiler & Flühler, 2004).

Flow type	Soil characteristic	Characteristic dye pattern	Proportion of stained path width for	
			<20 mm	>200 mm
Macropore flow with low interaction	Macropores in a low permeable or saturated soil matrix		>50 %	>20 %
Macropore flow with mixed interaction (high and low)	Macropores in a heterogeneous soil matrix or macropores with variable macropore flow		20-50 %	<20 %
Macropore flow with high interaction	Macropores in a permeable soil matrix		<20 %	<30%
Heterogeneous matrix flow and fingering	Spatially heterogeneous soil properties		<20 %	< 30-60%
Homogeneous matrix flow	Permeable soils		<20 %	<60 %

Tension infiltration measurements

Tension infiltrometers have also been widely used to understand soil hydraulic properties. An early tension infiltrometer was designed to evaluate the impact of soil air pressure on infiltration or irrigation (Dixon, 1975; Linden et al., 1977). After Clothier and White (1981) introduced a way of measuring soil sorptivity in a field, Watson and Luxmoore (1986) modified this method by using a tension infiltrometer. They evaluated that a tension infiltration test was simple and fast to investigate hydrologically active macropores in surface soils. A design of tension infiltrometers has been improved for more convenient and accurate usage. Ankeny et al. (1988) demonstrated an automated tension infiltrometer, and Perroux and White (1988) designed a disc infiltrometer. The disc infiltrometer is appropriate to estimate saturated hydraulic conductivity and flow-weighted pore dimension characteristics, so this is widely used today (Perroux & White, 1988). A number of equations assessing soil hydraulic conductivities have been suggested, and each equation requires a specific type and number of infiltrometers, and different kinds of infiltration data (Logsdon & Jaynes, 1993). For example, Logsdon and Jaynes (1993) provided a method which calculated saturated hydraulic conductivity from tension infiltration rates. Also, Bodhinayake et al. (2004) presented an equation for determining water conducting macroporosity and mesoporosity using tension infiltration data.

As increasing an interest in rock fragments, tension infiltrometers started to be used in a stony soil research. Brakensiek and Rawls (1994) suggested equations to calculate hydraulic parameters in stony soils by using tension infiltration rates. They assessed effects of rock fragment contents and rock fragment covers on the infiltration. Ma and Shao (2008) evaluated the impact of rock fragments on mineral soils and pore structures by comparing tension infiltration rates in the stony and nonstony soil. Verbist et al. (2012) concluded that a tension infiltration method is a good option for determining saturated hydraulic conductivity in stony soils.

Breakthrough curves

Breakthrough curves are commonly used for the advanced understanding of water drainage, infiltration rates, solute transport, and water accumulation in soils (Zhang et al., 2016). In particular, a breakthrough curve provides an efficient, fast, and accurate measurement of solute transport compared with other methods (Vanclooster et al., 1993). This is suitable to investigate the velocity of solute movement and the amount of solute leached in drainage or retained in soils (Strock et al., 2001; Vanclooster et al., 1993). Identifying a process of solute transport in agricultural soils is highly important to achieve an optimum application of fertiligers (Mojid et al., 2016).

One of the most common methods to obtain breakthrough curves is the use of time-domain reflectometry (TDR) techniques (Mallants et al., 1994; Mojid et al., 2016; Persson, 1997; Risler et al., 1996; Ritter et al., 2005; Vanclooster et al., 1993). A TDR technique can provide in-situ information of solute dispersion without disturbing soils (Mallants et al., 1994). The TDR methods are based on measuring soil Electrical Conductivity (EC) because solute concentration affects EC of soil and leachate. Figure 2.1 shows examples of breakthrough curves obtained by TDR. EC graphs increase rapidly at a certain time, and then decreses after drawing a peak. As comparing the time when the peaks appear, solute movement can be predicted. Analyzing solute concentration in leachate is also a common way of obtaining breakthrough curves of leachate.

Breakthrough curves have been used in stony soil studies. Strock et al. (2001) analyzed the concentration of solute tracers in water drainage to identify preferential flows in stony soils. Pang et al. (2017) investigated the movement of contaminants through stony soils by drawing a breakthrough curve of leachate. Carey et al. (2017) identified a nitrogen leaching from a winter forage grazing system by measuring a nitrogen concentration in drainage.

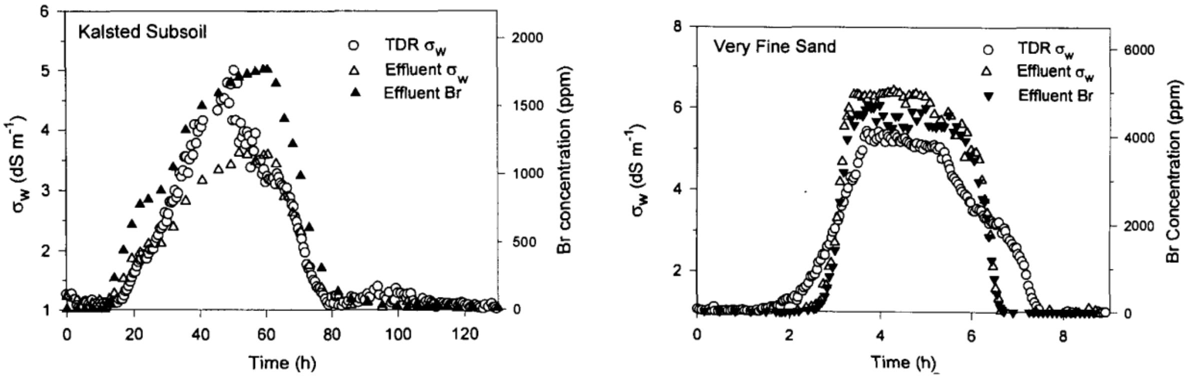


Figure 2.1. Examples of breakthrough curves obtained using TDR (Risler et al., 1996). The characteristics of breakthrough curves, including the location of peaks and the sharpness of curves, give the velocity and intensity of solute leaching.

2.4 Rock fragments and soil water movement

2.4.1 General soil hydrology

Basic water movement in soils was described by Kim et al. (2006). Figure 2.2 shows interpretation of general water flow in a soil. Precipitation and irrigation are the major sources of water input in a soil. Some of the water enters into soils, called infiltration, and the other water flows along a soil surface, called runoff. Soils lose some of the water by evaporation and transpiration. Infiltration rates, runoff, and evaporation depend on characteristics of a soil surface. Infiltrated water is redistributed horizontally or vertically in a soil by the gradient of soil water potential which includes matric, osmotic, pressure, and gravitational potential. Percolation is a downward flow of water, and interflow is horizontal water movement. Plant roots affect soil water flow by uptaking water, which influences the gradient of soil water potential. Absorbed water is released into the air at a leaf surface (transpiration). Some of the water recharges groundwater, and at the same time, groundwater is absorbed into a soil again by capillary rise.

Capillary power allows a soil to retain water in the space between soil particles. A capillary tension increases when a soil dries, so dry soil particles can hold water more tightly, which hinders water intake of plant roots. Wilting point is the soil water status that plants cannot extract water from a soil anymore. The maximum amount of water left in a soil after gravitational drainage is called field capacity. Plant available water is the soil water condition between field capacity and wilting point.

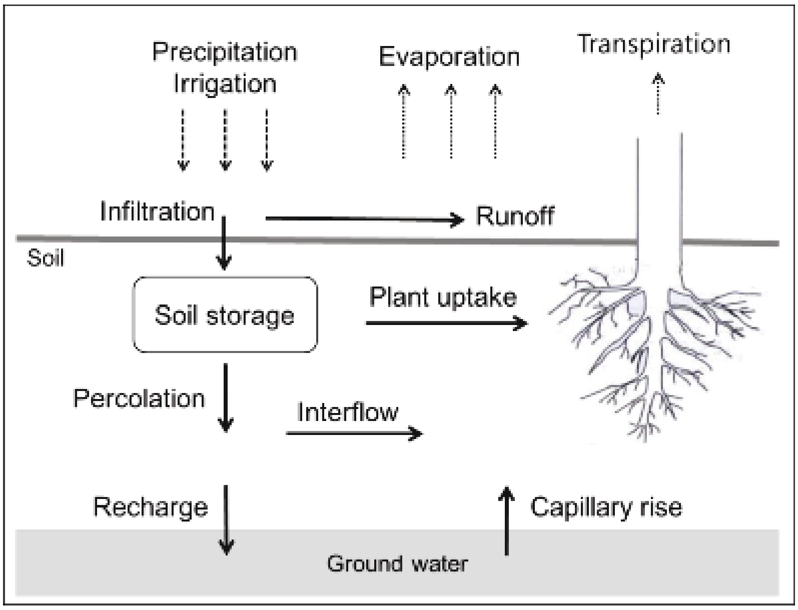


Figure 2.2. Interpretation of general soil hydrology (Kim et al, 2006).

2.4.2 Rock fragments and surface hydrological processes

Soil hydrology is extremely affected by the composition of soil particles (Rytter, 2012). Rock fragments in topsoil alter rainfall interception, infiltration rates, runoff, and evaporation of soils by absorbing and evaporating water from their surface, and creating water flow paths around them (Poesen & Lavee, 1994).

Previous research has shown inconsistent results in terms of the effect of rock fragments on surface water dynamics in soils. Rock fragments have been reported to accelerate water infiltration rates. Zavala et al. (2010) found a water column created between rock fragments increased water pressure on a soil surface and enhanced water infiltration. They also reported that rock fragments interrupted runoff flow, and this provided a more time for water to permeate into soils. Wang et al. (2012) suggested rock fragments covers protected a soil surface against rainfall drops and affected water runoff and infiltration rates. Zhang et al. (2016) also reported surface rock fragment covers could increase water infiltration and decrease runoff and evaporation rates. In addition, the effect of rock fragments on altering a pore structure can be more favourable to infiltration (Ma and Shao, 2008). However, according to Brakensiek and Rawls (1994), the relationship between rock fragments and water infiltration depends on rock fragment sizes; large rock fragments increased, and small rock fragments decreased water infiltration. Xia et al. (2018) also pointed out that small rock fragment covers more effectively decreased runoff rates and soil losses than large rock fragments. Ma and Shao (2008) reported high volumes of rock fragments decreased a cross-sectional area in soils which were available for water flow, and consequently, water infiltration decreased.

While Ma and Shao (2008) focused on the effect of rock fragment content, Sauer and Logsdon (2002) thgouth that infiltration rates were more related to sources of rock fragments than rock fragment content. Xia et al. (2018) reported a position of rock fragments, for example, partly or completely embedded in a soil surface, was more important than rock fragment coverages or sizes. Poeson and Lavee (1994) found rainfall interception, rock surface flow, infiltration, and evaporation rates were significantly affected by a position of rock fragments. Partly incorporated rock fragments more increased runoff rates than the rock fragments resting on a soil surface.

2.4.3 Rock fragments and subsoil water dynamics

Rock fragments have a much more significant effect on subsoil hydrology. Novák et al. (2011) found rock fragments decreased plant available water, water capacity, and hydraulic conductivity of soils. Urbanek and Shakesby (2009) pointed out the distribution and alignment of rock fragments are important to soil water flow. Rock fragments created continuous water flow paths along their surface (Figure 2.3), which enhanced water flow rates.

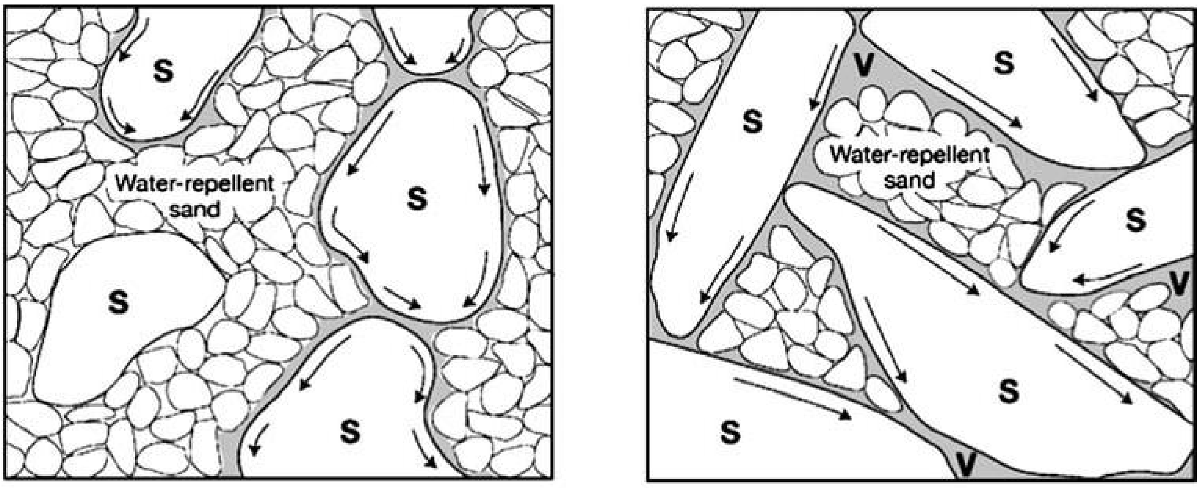


Figure 2.3. Description of water flow along a surface of stones (S) (Urbanek & Shakesby, 2009). The stones create continuous voids (V), which induces faster water flow.

Continuous pores are major preferential flow pathways. Preferential flow refers all flow mechanisms which transport water and dissolved solutes irregularly through certain pathways with bypassing other parts of the soil (Gerke, 2006). These pathways account for only a little fraction of total soil porosity (Allaire et al., 2009), so the other parts of the soil are remained dry (Gerke, 2006). Preferential flow is a common phenomenon caused by various reasons. Gerke (2006) attributed preferential flows to three main causes (Table 2.6). However, recent studies have reported rock fragments are also closely related to preferential flow. According to Novák and Kňava (2012), rock fragments could promote the deeper penetration of water in a soil with high hydraulic conductivity. In addition, rock fragments have an influence on soil compaction and root penetration which are also important causes of preferential flow (Schwärzel et al., 2012). Because water storage and water residence time in a soil decrease with occurring preferential flow (Dobrovolskaya, Chau, & Si, 2014), identifying the effect of rock fragments on preferential flow is critical. Reduced soil water retention decreases crop yields, so preferential flow has been a big concern in agricultural soils (Morales, Parlange, & Steenhuis, 2010). Besides, preferential flow results in inefficient use of fertilizer because solute transportation is also related to soil water flow. Hoskins et al. (2014) reported a leaching of tracer elements became much faster with the presence of rock fragments in a soil because of preferential flow. Di and Cameron (2002) found nitrate leaching increased with generating preferential flow. These results imply a high possibility of groundwater contamination with the presence of rock fragments.

On the other hand, soils near preferential flow paths have shown to contain a higher concentration of soil organic carbon and nitrogen, compared to the rest of the soil (Bundt et al., 2001). Higher nutrient accumulation in preferential flow paths enhanced microbial community (Bundt et al., 2001) and nitrogen transformation (Hagedorn et al., 1999). This could promote plant root growth, which would generate another preferential flow consequently. Despite this knowledge of the effect of rock fragments on generating preferential flow, studies on this topic are still scarce.

Table 2.6. Different types of preferential flows and their causes (Gerke, 2006)

Types	Causes
Macropore flow	Root channel, earthworm burrows, fissures, cracks
Unstable flow	Instable wetting front caused by soil textural layering, water repellency, or air entrapment
Funnel flow	Textural boundaries converted to a less permeable zone

The existence of rock fragments in a soil was reported to reduce the water capacity and hydraulic conductivity of the soil (Novák & Kňava, 2012). However, Novák and Šurda (2010) pointed out that the reduced hydraulic conductivity of soils by rock fragments increased the water residence time and water storage of soils. Marion et al. (2015) also found rock fragments in a soil acted as a water reservoir which released water more slowly, so they said the role of rock fragments in a soil had to be reconsidered. These studies indicate rock fragments can result in more favourable soil water condition for plants.

There have been conflicting results about the influence of rock fragments on the saturated hydraulic conductivity of soils. Bouwer and Rice (1984) found increasing rock fragment content from

0 % to 70 % in a soil decreased saturated hydraulic conductivity. In contrast, Beckers et al. (2016) reported the positive relationship between rock fragment content and saturated hydraulic conductivity. Differently, Beibei et al. (2009) found saturated hydraulic conductivity decreased with increasing rock fragment content from 0 % to 40 %, but the values increased when rock fragment content was over 40 %. Different again, Ma et al. (2010) said there was no relationship between saturated hydraulic conductivity and rock fragment content. They pointed out rock fragments should not be always considered as a non-porous media, so there were various effects of rock fragment on soil water flow. In a repacked soil column study, the packing condition of soils is also one of the important factors to soil water flow, particularly when rock fragment content was between 40 % and 80 % (Zhang et al., 2011).

The in-situ measurement of saturated hydraulic conductivity in a stony soil has also shown irregular results. Khetdan et al. (2017) found that saturated hydraulic conductivity decreased when rock fragment content increased from 0 % to 20 %. However, the value increased with increasing rock fragment content from 20 % to 60 %. Differently, Sauer and Logsdon (2002) reported there was no significant relationship between rock fragments and saturated hydraulic conductivity. Literature interpreting an impact of rock fragments on a soil hydrological process are still scarce (Novák & Kňava, 2012). Moreover, the literature showed inconsistent or contrasting results depending on soil materials and the surrounding environment of experimental sites. The relationship between rock fragments and soil water flow is still under debate, and this literature review indicates that investigation of the role of rock fragments in water flow using Eyrewell soil would be highly valuable.

2.5 Rock fragments and soil physicochemical properties

2.5.1 Influence on soil physical properties

Bulk density is commonly measured to estimate soil compaction (Page-Dumroese et al., 1999). Soil bulk density is strongly related to soil infiltration rates, aeration, root proliferation, and plant growth (Throop et al., 2012). Many studies demonstrated the effect of rock fragments on soil bulk density. According to Stewart et al. (1975), a high amount of rock fragments in a soil decreased soil bulk density by creating a huge space between soil particles and rock fragments. Khetdan et al. (2017) reported that a looser mineral soil at the surface of rock fragments induced a negative relationship between rock fragment content and mineral soil bulk density in a field. Different to this, Rücknagel et al., 2013) insisted rock fragments acted as a supporting frame and protected mineral soils from compaction. The effect of rock fragments on decreasing soil compaction has been found to be advantageous to plant root growth in a highly compacted soil (Poesen & Lavee, 1994).

Determining accurate bulk density is exceedingly difficult in a soil containing rock fragments because rock fragments interfere with an undisturbed soil core sampling (Stewart et al., 1975). Page-Dumroese et al. (1999) suggested a couple of methods available to measure the bulk density of stony soil; core sampling, excavation and volume determination, and radiation. A core sampling method is the most simple way to examine bulk density, but this method underestimates bulk density when a core is obstructed by a large stone (Flint & Childs, 1984). At the same time, the core sampling could overestimate bulk density if core hammering increases soil compaction (Page-Dumroese et al., 1999). An excavation and volume determination method is a more useful alternative to the core sampling because the large sample size of this method reduced the variability of samples (Page-Dumroese et al., 1999). In a field study of stony soils, a large sample size is very important to estimate the hydraulic properties of soils (Novák & Kňava, 2012). On the other hand, a radiation method enables to measure the bulk density of subsoil without soil disturbance, so continuous and repeated measurements are possible in a sampling zone (Blake & Hartge, 1986). This method needs to be corrected by rock fragment contents, however, variable rock fragment content in the sampling zone is usuall problematic (Flint & Childs, 1984).

Rock fragments also have a huge impact on the soil pore system. A pore system is a critical factor to decide entire soil characteristics. Soil pores are the major pathways of soil water transport. Generally, a study on soil water flow interprets with a macroscopic scale, but investigation of soil pores enables a quantitative microscopic explanation of water flow (Novák & Kňava, 2012). Soil porosity can be classified by a diameter; micro-, meso- and macroporosity. Table 2.7 presented three types of soil porosity and their principal functions categorized by Luxmoore (1981). Although water flows faster through a large pore, an increase in macroporosity does not always generate a rapid water flow through a soil (Bodhinayake et al., 2004). This is because the continuity of macropore is more important to water flow rates. Continuous pores, also called conducting pores or active pores, enhance the velocity of water flow whereas isolated pores interrupt water movement by trapping air (Beibei et al., 2009). Furthermore, water flow does not occur once the isolated pores are saturated.

Table 2.7. Three sizes of soil porosity and their principal functions (Luxmoore, 1981).

Soil porosity	Equivalent pore size (μm)	Principal function
Micoroporosity	< 10	Evapotranspiration
Mesoporosity	10 - 1,000	Drainage
Macroporosity	> 1,000	Channel flow

There have been many studies focused on the impact of rock fragments on soil porosity. Rock fragments were usually impermeable, so rock fragments reduced soil porosity when they accounted for space instead of mineral soils (Mehuys et al., 1975). In contrast, small size gravels (1.7-2.7 cm) increased the macroporosity of topsoil in the research of van Wesemael et al. (1995). The pore system of stony soils could be investigated by binary mixture studies which contained two different sized particles. According to Zhang et al. (2011), volume percentages of constituents and their diameter ratios were significantly important to decide the total porosity of the binary mixture. When a volume of large particles excessed small particles, the size of pores increased (Sakaki & Smits, 2015). When two different sized particles were mixed, smaller particles could fill the space between larger particles in a binary mixture. As a result, the total porosity of a binary mixture was always smaller than the sum of 'porosity of small particle' and 'porosity of large particle' (Zhang et al., 2011).

2.5.2 Influence on soil chemical properties

There have been some debates on the effect of rock fragments on soil chemical properties. Cerdà (2001) found rock fragments on the soil surface increased soil organic matter. However, according to De Baets et al. (2013), increasing rock fragment content decreases soil organic matter. Qin et al. (2015) also reported rock fragments decreased both soil organic carbon and total nitrogen. Different to this, Meersmans et al. (2012) considered that the effect of rock fragments depended on soil texture. They found a positive relationship between rock fragment content and organic matters in a silt dominated soil, but the relationship was negative in a coarser textured soil.

Various mechanisms have been suggested as to how rock fragments affect soil chemistry. Rytter (2012) thought that rock fragments physically reduce the capacity of soils to retain the air, moisture, and nutrients by taking space in place of mineral soils. According to Poesen and Lavee (1994), rock fragments affected soil moisture and soil temperature, which are closely related to the microbial activity (Wu et al., 2012). Microbial activity is highly related to organic matter decomposition, mineralization, and nutrient recycling (Huang et al., 2013; Tripathy et al., 2014). Qin et al. (2015) found the interface between rock fragments and mineral soil provided a favourable condition for microorganisms to degrade organic matters. Certini et al. (2004) also demonstrated rock fragments increased microbial activity.

From a different consideration, preferential flow generated by rock fragments enables increased nutrient content in the soil near rock fragments. This flow has been forward to increase nutrient supply and nitrogen transformation in the soils around flow pathways (Bundt, Jäggi, et al., 2001; Bundt, Widmer, et al., 2001; Hagedorn et al., 1999). However, the preferential flow could increase nutrient leaching as described in the previous section, and the lower nutrient-holding capacity of stony soils decreases overall soil fertility (Di & Cameron, 2002).

The influence of rock fragments on soil physicochemical properties clearly requires future study and elucidation. In New Zealand, only a limited number of studies have been carried out on the relationship between stony soils and soil properties. An investigation of the relationship between soil properties and rock fragments in Eyrewell soil in the present study appears to be well justified.

2.6 Rock fragments and plants

2.6.1 Influence on plant growth

Altered soil properties, as caused by rock fragments, obviously have an impact on plant growth. Increased or decreased soil compaction by rock fragments affects plant root penetration and plant productivity (Schwärzel et al., 2012). Rock fragments negatively influence root extension by reducing space for root penetration (Estrada-Medina et al., 2013; Nie et al.,2014). Aboveground plant biomass has also been shown to decrease with the presence of rock fragments (Qin et al., 2015; Wu et al., 2012; Yang et al., 2009). Plants in a highly stony soil had shorter heights, thinner basal stems, and fewer leaves and roots (Mi et al., 2016). Bornyasz et al. (2005) pointed out that the lower nutrient capacity of a stony soil hindered plant growth. However, many studies have obtained the opposite results. Van Wesemael et al. (1995) reported lower mineral soil bulk density around rock fragments encouraged root penetration ability. Rytter (2012) found higher fine root density around rock fragments because preferential flow caused by rock fragments induced higher nutrient supply. Danalatos et al. (1995) and Heisneret al. (2004) reported rock fragments increased aboveground biomass. In the study of Novák and Šurda (2010), rock fragments helped plant survival during a dry season by decreasing the hydraulic conductivity of a soil and increasing water residence time. Danalatos et al. (1995) also reported rock fragments increased wheat productivity in a dry period by maintaining soil moisture. The effect of rock fragments on soil temperature also has an impact. Rock fragments increased soil temperature more rapidly at the beginning of spring and maintained the warm temperature for a long time (Poesen & Lavee, 1994). In turn, higher temperature can improve root development (Du et al., 2017). Wang et al. (2011) also demonstrated that gravel mulch provided more favourable soil thermal conditions for plant growth.

The roles of rock fragments in conserving soil moisture and protecting a soil surface from erosion had a positive influence on crop yields (Nyssen et al., 2001). However, only a few studies have investigated the relationship between rock fragment content and plant productivity (Poesen & Lavee, 1994). Moreover, plant growth is highly influenced by other factors, such as soil texture, nutrient status, climate, and vegetation types, so the studies on this topic showed regionally variable results (Poesen & Lavee, 1994). More area-specific research is certainly required.

2.6.2 Combined influence of rock fragments and plants on soil hydrology

The effect of rock fragments on plant growth indirectly affects soil hydrology, and water flow and nutrient dynamics in soil are significantly associated with the presence of plants. Plants can intercept rainfall before it reaches on the ground. Trees act as channels or water conduits which localise the deposition of precipitation to the ground surface (Johnson & Lehmann, 2006). Rainfall flows along leaf surfaces, stems, and trunks and then goes into the ground following plant root channels (Johnson & Lehmann, 2006). Plant roots provide one of the major preferential flow pathways. According to Devitt and Smith (2002), plant stems and roots create water paths of soil water infiltration and percolation. Schwärzel et al. (2012) also demonstrated that plant roots enhanced the development of lateral subsurface flow. Plant rhizospheres uptake water or retain water in a root zone, and this highly affects soil water movement (Carminati et al., 2010). Some studies have reported plant rhizosphere could increase water residence time in soils. According to Young (1995), soil water content was higher with the presence of plant roots. Carminati et al. (2010) pointed out that mucilage exuded from plant roots helped to conserve higher soil moisture because extracellular polysaccharides, which forms the main component of mucilage, increase water residence time in soils (Chenu, 1993). The role of rhizosphere is a buffer or a hydraulic connector between soil particles and plant roots, which contributes to reducing a hydraulic stress of roots during dry periods (Carminati et al., 2010). In addition, plant roots can increase microorganisms by providing nutrition sources (Kremer et al., 2005), which also may be related to soil hydrology. Root exudates significantly stimulate microbial population and their activity because the exudates are an easy-assimilated source for microorganisms (Kraffczyk et al., 1984).

2.7 Conclusion

Studies of the effects of rock fragments on soil water flow, soil properties, and plant growth are inconsistent. Previous results have proven to be variable and dependent on regional variation, environmental conditions, and experimental variables. Furthermore, rock fragments, soils, soil water, and plants are closely related, which makes the study of rock fragments more complicated. Despite the obvious significance of rock fragments, studies on New Zealand stony soil are very scarce. A study on the effect of rock fragment on the stony soil at Te Whenua Hou is likely to be highly valuable for successful soil management both to dairy farm development and ecological restoration in this landscape that is being converted from plantation forest.

Chapter 3

A field study on current water flow patterns at Te Whenua Hou

3.1 Introduction

A technique of dye application has been used previously to investigate water flow in soils containing rock fragments. A dye tracer which visualizes water flow allows to assess the role of site-specific soil features in water movements (Alaoui & Goetz, 2008; Anderson et al., 2009; Laine-Kaulio et al., 2015; Schwärzel et al., 2012; Y. Wang & Zhang, 2017; Weiler & Flühler, 2004). With this technique, the dye tracer is applied on soil surfaces, and adjacent soil profiles are excavated to observe water movement (Weiler & Flühler, 2004). A distinct colour of dye is helpful to contrast against background soil colours (Devitt & Smith, 2002). The dye flows through continuous pores, so this technique is particularly useful to study preferential flow (Droogers et al., 1998). Moreover, the dye tracer is inexpensive and not toxic to the environment (Allaire et al., 2009). One of the drawbacks is that dye experiments cannot be replicated at the same site because soil structures are destroyed by excavation (Flury & Flühler, 1994b), but this technique is useful to identify complex spatial water flow patterns (Flury & Flühler, 1994b). There is no standard approach to interpret and quantify dye patterns in soils (Droogers et al., 1998; Weiler & Flühler, 2004), but recently a digital image processing method has been used to quantify dye coverage areas (Alaoui & Goetz, 2008; Flury & Flühler, 1994b; Laine-Kaulio et al., 2015; Wang & Zhang, 2017; Weiler & Flühler, 2004).

Eyrewell soil is stony, compacted, and very dry. Soils containing rock fragments have a lesser capacity to hold water because rock fragments occupy space in place of mineral soil. This constrains the survival, establishment and growth of plants. This chapter aims to identify (i) current features of Eyrewell soil, (ii) general water flow patterns in Eyrewell soil, and (iii) effects of soil characteristics on in-situ water flows, by combining a dye technique with laboratory analysis.

3.2 Methods

3.2.1 Site information

Figure 3.1 shows the locations of the three experimental sites in a south-west corner of Farm 14. To avoid farmlands and restoration areas, sites located on farm margins were chosen. This margin was bordered by a forestry block, a dairy farm, and a newly developed gravel road. Vegetation consisted of wayside grasses and herbs, wilding pine, and broom. The soil in this area has been historically disturbed as explained in Chapter 1.1, but not by the recent conversion. Three sites were selected as representatives of three different degrees of soil disturbance by the land conversion. Site 1 was located near a fence of the pine forest, which had not been little influenced by the conversion. Site 2 was near the road, which had been moereately disturbed. Site 3 was close to the dairy pasture, where was entirely affected by the conversion. The distances between the sites were about 100-150 m.

Figure 3.1. The location of study sites in Eyrewell dairy farms. Three sites were in the same paddock, the margin of Farm 14, and each site was located near the pine forest, the road, and the dairy pasture.

3.2.2 Sample collection

Soil samples were collected from each of the three sites with a volume of 18000 cm^3 (width 30 x length 30 x depth 20 cm) at different depths in the soil profiles, to analyse soil physical and chemical properties. Four depths were collected at each site (0-20, 20-40, 40-60 and 60-80 cm). As the Eyrewell soil is highly stony and compacted, digging soils from surfaces was too difficult, so deep and wide pits of 2 m depth were dug in advance using an excavator (Figure 3.2). Soil samples were collected from the wall of the pit by carefully excavating from the side (Figure 3.3). Collected samples containing all soil and rock fragments were then tansfered to a laboratory for analysis. This collection was carried out on March in 2015.

3.2.3 Dye application

A scheme of dye application experiment is illustrated in Figure 3.3. A dye tracer was applied using a ponding method adjacent to the soil sampling spots at the three sites. There was no rainfall in a week before dye application, so the soil was relatively dry. Prior to the dye application, vegetation was removed, and soil surface was leveled. Berms (1 m x 1 m) were created using bentonite clays at edges of an application plot in order to avoid surface runoff of the dye and to allow ponding. Total 40 L (40 mm in depth) of Brilliant Blue FCF was applied for each site at a concentration of 3 g L^{-1}; this is a color tracer which has good visibility, high mobility, and low toxicity (Flury & Flühler, 1994a). The application plot was then covered by a plastic to minimize evaporation and surface disturbance. After 48 hours, the soils under the application plot were excavated vertically and exposed cross-section areas were photographed under daylight conditions (see Figure 3.3). The vertical excavation was conducted four times with 20 cm intervals apart from one side wall of the pit, finally, four verticle cross-sections in distance of 20, 40, 60, and 80 cm from the wall were observed. When the cross-sections were photographed, a yellow frame (1 m × 1 m) was attached foe scale.

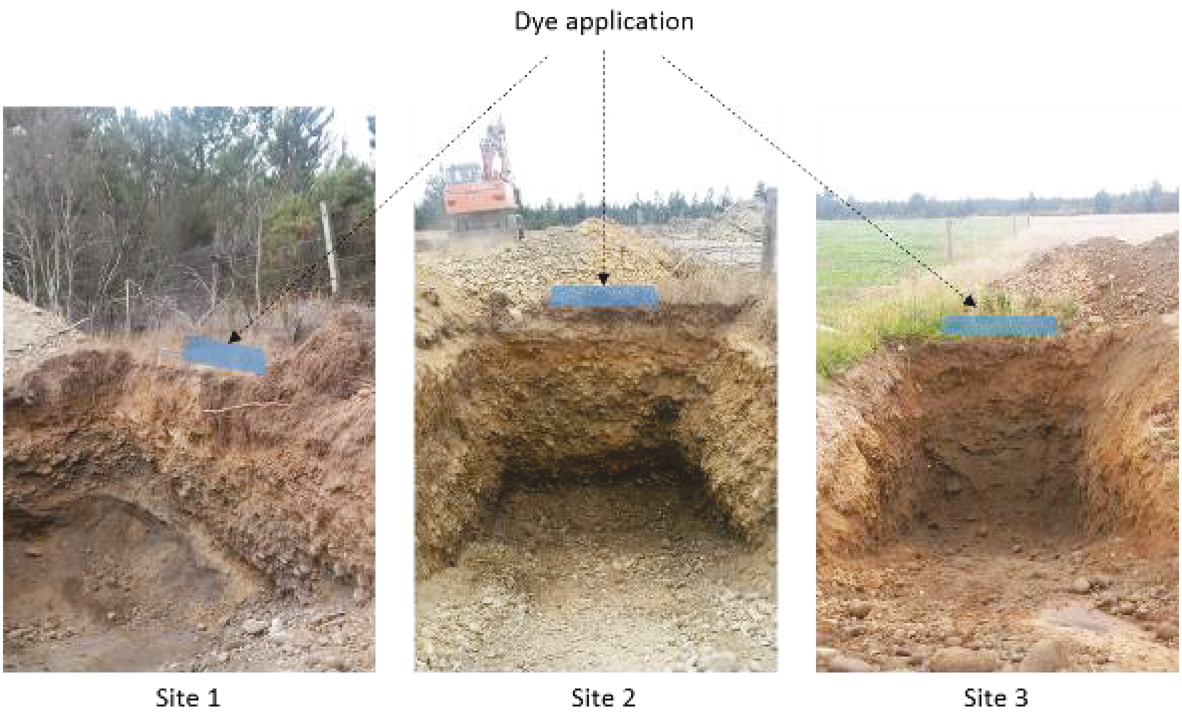


Figure 3.2. Excavated pits in three experimental sites. The pits were created prior to soil collection and dye application to make excavation easier. Site 1 was near the pine forest. Site 2 was near the new built road. Site 3 was near the dairy pasture.

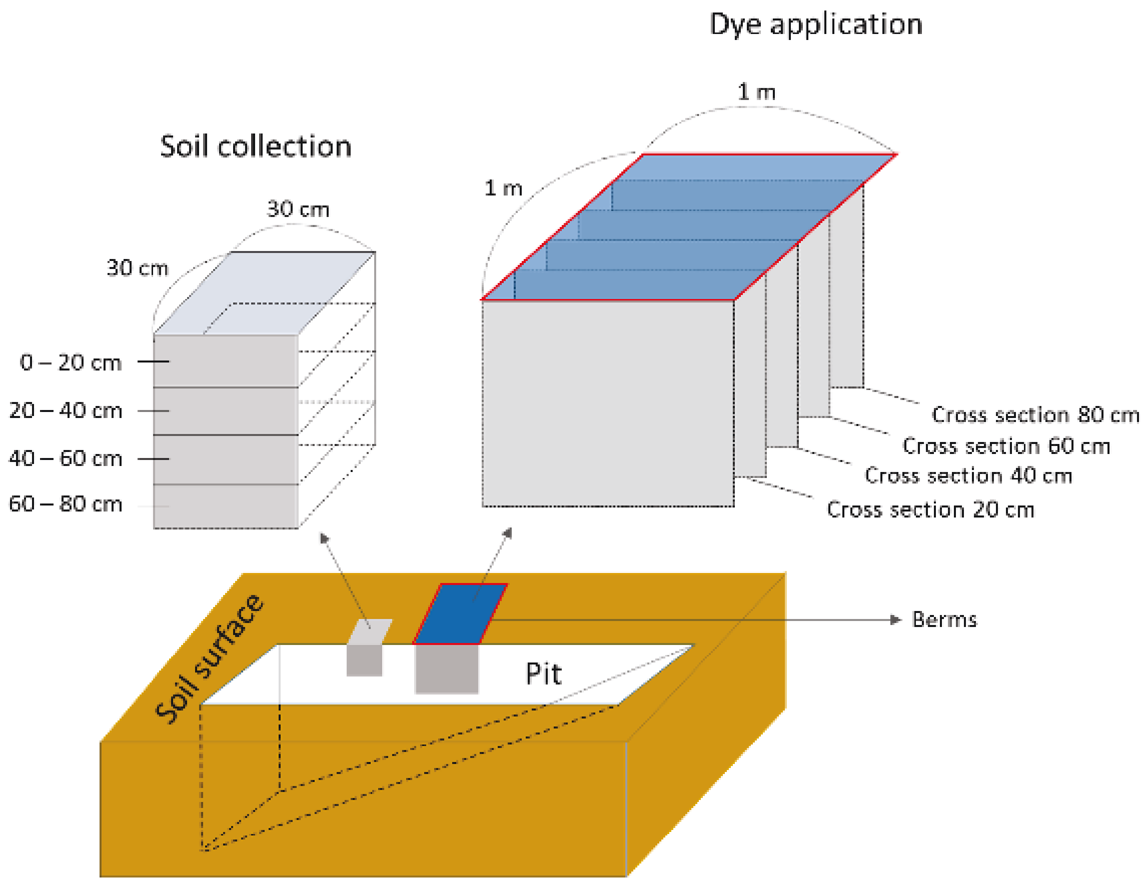


Figure 3.3. Scheme of experiment. Soil collection and dye application were conducted at one side wall of each pit. Soil samples were collected by every 20 cm depth. After the dye application, the soil was vertically excavated at 20 cm intervals.

3.2.4 Rock fragment contents, size, and number

Rock fragment content in the soil samples was analysed. Following the rock fragment classification in Figure 3.4, a soil particle smaller than 2 mm in diameter is a mineral soil, 2-76 mm is a gravel, and 76-200 mm is a stone (Miller & Guthrie, 1984). A rock fragment refers all particles larger than 2 mm in diameter.

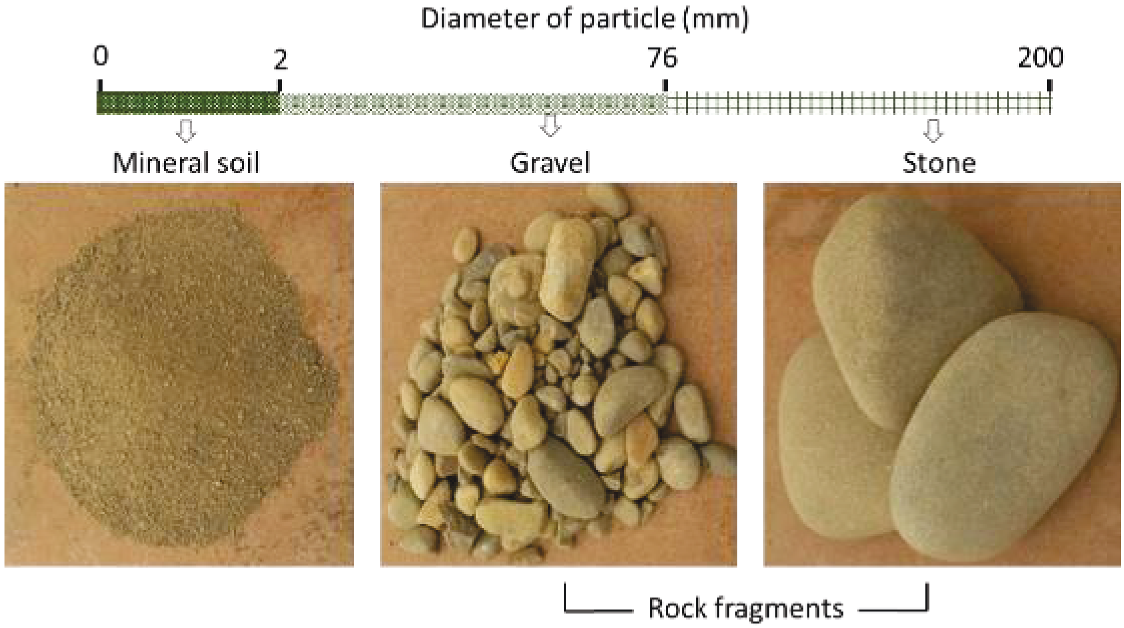


Figure 3.4. Rock fragment classification. Rock fragment refers to soil particle larger than 2 mm in diameter while mineral soil is smaller than 2 mm. The rock fragment is divided into two groups again, a gravel (2-76 mm in diameter) and a stone (76 – 200 mm in diameter).

Collected soil samples were dried in an oven at 30 ℃ for three days, stones were extracted by hand and kept in a separated bag. The rest of the sample was sieved using a 2 mm sieve. Mineral soils which passed through the sieve were stored separately. The particles which remained on the sieve including gravels and aggregated mineral soil were sieved again after the aggregated soils were broken down by rolling with a heavy stainless steel rod. The same process was repeated until the aggregate soils were not observed anymore. After the samples were completely separated into three groups of particles, a weight of each group was obtained. The longest diameter of stone in each sample was measured using a caliper and the number of stones was counted. Volumes of rock fragments were estimated by dividing weights (g) by particle density. The particle density of rock fragments was assumed to be 2.65 g cm^{-3} which is an average value (Brakensiek & Rawls, 1994; Khetdan et al., 2017; Page-Dumroese et al., 1999). After then, percentages of rock fragments was calculated by dividing the volume of rock fragment by the volume of whole soil sample (18000 cm^3).

3.2.5 Soil texture

Soil texture was analysed using a micro-pipette method following Miller and Miller (1987). 2 g of mineral soil was mixed with 40 ml of dispersion reagent which was a litre of mixture containing 10 ml of 1 M sodium hydroxide (NaOH) and 10 ml of 5 % sodium hexametaphosphate ($NaPO_3$). The soil and reagent were mixed well using an end-over-end shaker for more than 12 hours. After dispersing, the mixture was placed in an incubator at 30 ℃ for 1 hour 56 minutes 3 seconds. Then 2.5 ml of the mixture sample was taken with a pipette at a 2.5 cm depth from a surface of the mixture. The same amount of dispersing reagent was also taken to measure a background weight of the reagent. The sample and the reagent were dried in a drying oven at 105 ℃ and weighed. The rest of the mixture was passed through a 53 µm sieve to analyze a percentage of sands. The particles remained on the sieve were dried at the same temperature, and weighed. Clay, silt, and sand contents were calculated with following equations.

$$\text{Clay (\%)} = \frac{(Wc - Wr) \times 40}{2.5 \times 2} \times 100$$

$$\text{Sand (\%)} = \frac{Ws}{2} \times 100$$

$$\text{Silt (\%)} = 100 - \text{Clay (\%)} - \text{Sand (\%)}$$

W_c is the dry weight of 2.5 ml sample and W_r is the dry weight of 2.5 ml reagent. W_s is the dry weight of sand fraction. Then, soil texture was determined by a soil classificaiton system of the United States Department of Agriculture (USDA). Soil texture analysis were repeated three times and mean values of three replicates were shown.

3.2.6 Mineral soil bulk density

A common method to determine soil bulk density would be a core sampling method. However, it was very difficult to collect core samples from Eyrewell soil because of high stoniness. Measuring accurate soil bulk density in a stony soil is extremely hard, so alternatively, bulk density was calculated using an excavated method as listed (Page-Dumroese et al., 1999).

$$\text{Mineral soil bulk density} = \frac{\textit{Weight of oven dried mineral soil}}{\textit{Volume of mineral soil}}$$

The volume of mineral soil was estimated by deducting a volume of rock fragments from an original sample volume (18000 cm^3). This soil excavation method has been previously used as an easier and more useful way to measure soil bulk density than core sampling in stony soils due to a large sample size and low sample variability (Page-Dumroese et al., 1999).

3.2.7 Soil organic matter

Soil organic matter was determined by weight loss on ignition. Approximately 10-20 g of air-dried soil samples were dried in a drying oven at 105 ℃ for 24 hours. The oven-dried soil was weighed using a balance, and the soil sample was combusted in a muffle furnace at 550 ℃ for 4 hours. The combusted sample was weighed, and soil organic matter was calculated using the equation.

$$\text{SOM (\%)} = \frac{Wo - Wm}{Wo} \times 100$$

SOM is soil organic matter. W_o is oven-dried soil weight, and W_m is muffle-combusted soil weight.

3.2.8 Digital image processing and dye coverage

A digital image analysis was conducted to quantify dye coverage area in soil profiles. A blue colour of dyes was distinguished from a background soil by converting the blue into red (Figure 3.5) using Image J software (National Institute of Mental Health, USA) as a previous study (Wang & Zhang, 2017). The software could measure a percentage of red sections in a selected area. By controlling ranges of hue, saturation, and brightness of photographs, dyed areas changed to red as shown in Figure 3.6; the hue was ranged from 31 to 255, the saturation was from 0 to 186, and the brightness was from 30 to 162. The software was not sensitive enough to pick the dye stains under a dark colour of shadows, however, this area was small so it did not have a significant impact on results. After image processing, a percentage of red areas was recorded for every 20 cm of depth.

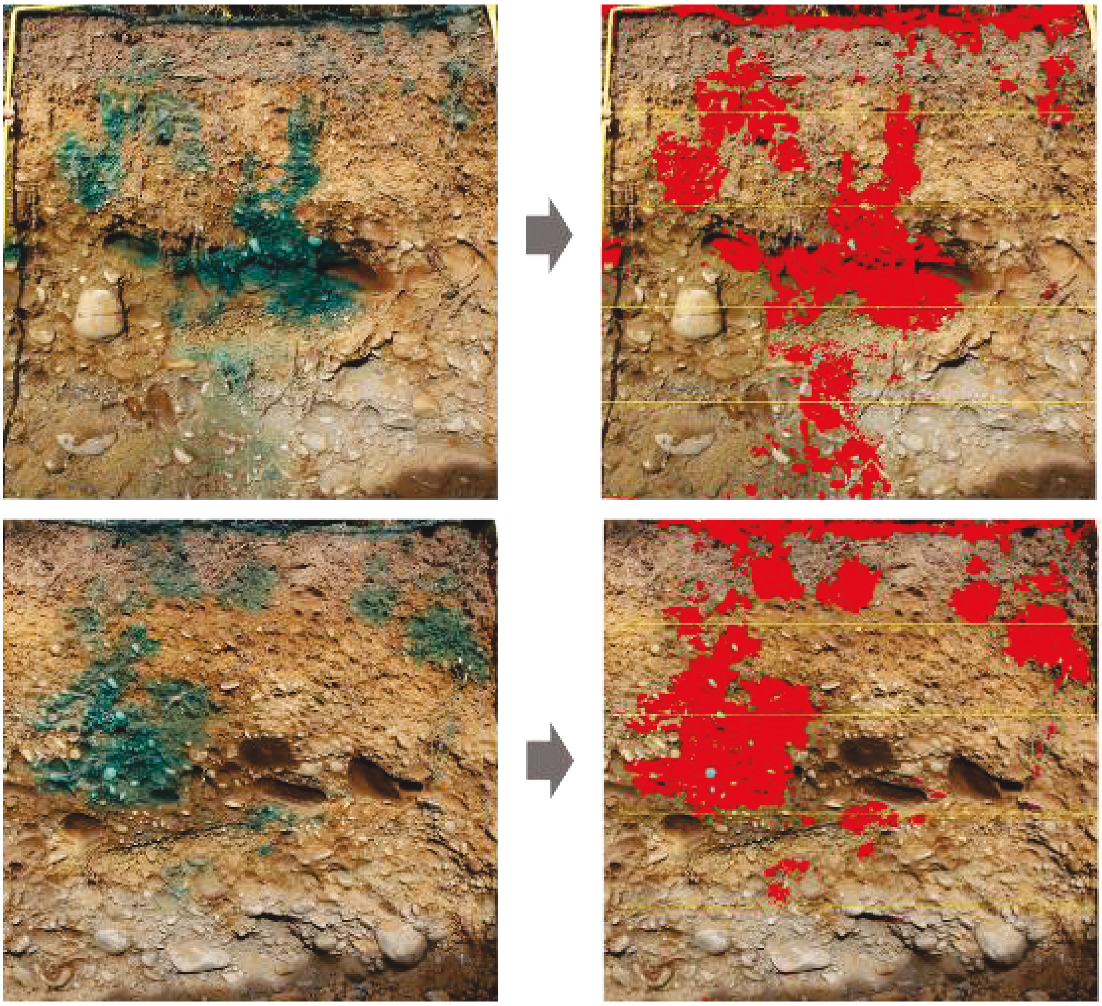


Figure 3.5. Distinguishing dye stains from background soil by converting the blue into red using Image J.

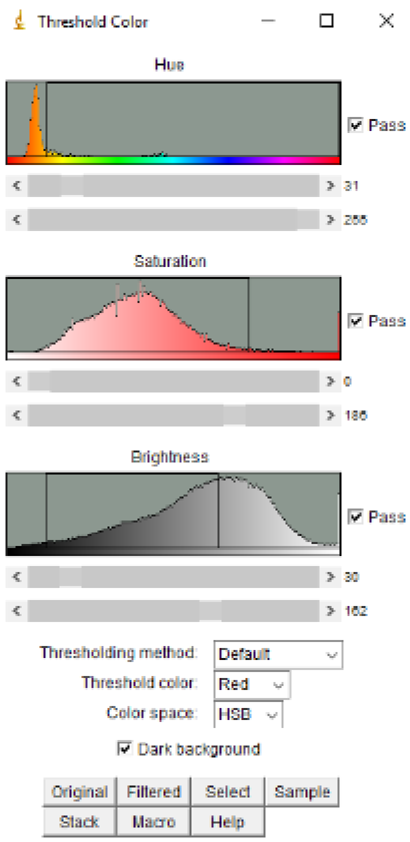


Figure 3.6. A colour thresholding window of Image J (National Institute of Mental Health, USA). Every photograph was adjusting to 31-255 in hue, 0-186 in saturation, and 30-162 in brightness.

3.3 Results

3.3.1 Soil properties

Rock fragment analysis

There was variation in rock fragment content across the three experimental sites and with depths (Table 3.1). All the sites showed the highest mineral soil content in topsoil. In Site 1, mineral soil contents decreased with increasing depth, particularly below 40 cm. The mineral soil content was only 8.5 % at 40-60 cm and 2.9 % in 60-80 cm depth at Site 1, which means the rock fragments occupied most of the space in these layers. Site 2 also showed the incrase in the rock fragment content below 40 cm, but the content was much less than Site 1. However, at Site 3, the rock fragment content was similar from 20 cm to 80 cm depth. In addition, the highest stone content was only 11.6 % at Site 3 while this was more than 30 % at Site 1 and 2.

Table 3.2 shows the largest diameter of stones and the total number of stones in each site by depth. A deeper soil (40-80 cm) contained a larger stone at Site 1 and 2 whereas Site 3 contained the longest stone in 20-40 cm depth. The number of stones was the smallest at Site 3, which was consistent to the lowest stone content at this site (Table 3.1). Site 1 showed a remarkable increase in the number of stones in 60-80 cm depth while Site 2 showed the relatively higher number of stones below 20 cm.

Table 3.1. Volume percentages of stone, gravel, and mineral soil by depth in three sites. Patterned bars visually present the percentages.

Depth (cm)	Classification	Site 1	Site 2	Site 3
		------------------	%	------------------
0-20	Mineral soil	66.9	84.5	57.5
	Gravel	30.1	14.2	41.2
	Stone	3.0	1.4	1.3
20-40	Mineral soil	53.2	52.4	41.9
	Gravel	45.4	30.5	46.5
	Stone	1.4	17.2	11.6
40-60	Mineral soil	8.5	30.3	43.0
	Gravel	81.8	38.5	48.5
	Stone	9.8	31.2	8.6
60-80	Mineral soil	2.9	33.8	40.2
	Gravel	63.6	47.5	54.9
	Stone	33.5	18.8	4.9

Mineral soil Gravel Stone

Table 3.2. The longest diameter of stones and the number of stones by depth in three site.

Depth (cm)	Site 1		Site 2		Site 3	
	Diameter[1] (mm)	Numbers	Diameter (mm)	Numbers	Diameter (mm)	Numbers
0-20	122.9	4	82.9	2	84.7	4
20-40	95.4	3	123.6	27	142.3	8
40-60	167.0	8	151.2	49	113.6	19
60-80	200.3	36	142.8	30	113.2	7

Mineral soil properties

Soils at 0-20 cm depth were loam in all sites (Table 3.3). Overall in all sites, sand contents increased gradually by depth while clay contents were reduced. While site 2 and 3 showed the same soil texture below 40 cm, this was gradually coarser from loamy sand to sand at Site 1.

At Site 1, the bulk density at 0-20 cm and 20-40 cm depth was much lower than the deeper layers (Table 3.4). The bulk density of 40-60 cm and 60-80 cm soil (8.5 and 15.0 g cm^{-3} respectively) are not reasonable values because mineral soil bulk density is usually between 1 to 2 g cm^{-3}. As described in 3.2.6, mineral soil bulk density was calculated by dividing a weight of mineral soil with an estimated volume of mineral soil. Errors seemed to be due to underestimation of the mineral soil volume. This means a volume of rock fragments was overestimated because the volume of mineral soil was calculated by deducting a volume of rock fragments from a whole sample volume of 18000 cm^3. There are two possible explanations:

i) All rock fragments which were located on a boundary of sample collection cubes were collected because they could not be cut. This means the volume of the collected rock fragments were actually bigger than actual because they included the parts which were out of the boundary. Consequently, the volume of mineral soil was underestimated.

ii) A volume of rock fragments was estimated by dividing a weight of rock fragments with an assumed particle density of rock fragments of 2.65 g cm^{-3}. If the particle density of Eyrewell rock fragments is higher than 2.65 g cm^{-3}, the volume of rock fragments could be overestimated, and consequently, a volume of mineral soil would be underestimated.

Usually, such errors are negligible, but extremely high amounts of rock fragments affected results at 40-60cm and 60-80cm depths at Site 1. Even though the bulk density of these layers was not accurately derived, it is certain that their mineral soils were extremely compacted as these soils were much harder to dig during sample collection.

Topsoil at Site 2 showed the lowest bulk density than the other depths. The bulk density increased almost twice at 20-40 cm soil but decreased at 40-60 cm soil, and mineral soils in the last layer appeared to be the most compacted. On the other hand, at Site 3, there was no clear change of bulk density with depth. Topsoil at Site 3 had the highest mineral soil bulk density among the three sites. High compaction in surface soils was likely to be mostly influenced by heavy machines during a land conversion.

Different to the other soil properties, organic matter contents showed a similar pattern in the three experimental sites; organic matter content gradually decreased with depth (Table 3.4).

Table 3.3. Particle size distribution and soil texture by depth in three sites. Each values are the mean of three replicates.

Depth (cm)	Classification	Site 1		Site 2		Site 3	
		%	Texture	%	Texture	%	Texture
0-20	Clay	11.0	Loam	10.3	Loam	14.0	Loam
	Silt	46.6		49.1		47.1	
	Sand	42.4		40.6		38.9	
20-40	Clay	10.3	Sandy loam	15.1	Loam	10.2	Sandy loam
	Silt	31.2		46.5		15.5	
	Sand	58.5		38.3		74.2	
40-60	Clay	5.1	Loamy sand	5.6	Loamy sand	4.3	Loamy sand
	Silt	11.7		16.9		9.6	
	Sand	83.2		77.5		86.1	
60-80	Clay	3.2	Sand	3.7	Loamy sand	3.5	Loamy sand
	Silt	4.7		10.6		9.9	
	Sand	92.0		85.8		86.6	

Table 3.4. Bulk density and organic matter contents of mineral soils by depth in three sites.

Depth (cm)	Site 1		Site 2		Site 3	
	BD[1]	SOM[2]	BD	SOM	BD	SOM
0-20	0.8	9.9	0.6	7.9	1.2	7.3
20-40	0.5	5.8	1.1	4.7	1.1	4.0
40-60	8.5[3]	3.2	0.9	3.0	1.2	2.9
60-80	15.0[3]	2.2	1.2	2.4	1.4	2.6

[1]Bulk density of mineral soil (g cm^{-3})
[2]Soil organic matter (%)
[3]Impossible values for bulk density. Explained in the text.

3.3.2 Visualized water flow patterns

Water flow at Site 1

Figure 3.7 shows soil cross-sections under a dye application plot at Site 1. Visually, higher amounts of rock fragments were concentrated at deep soils, and some were very large. There were hollowed areas where rock fragments were removed during excavation. Water flows were irregular in all soil profiles, bypassing most of the soil. Infiltration mostly occurred in cross-section 80 cm, which had high dye coverage of topsoil (Figure 3.8). The infiltrated water at the cross-section 80 cm percolated uniformly, perched at the depth of 20 cm, and started flowing irregularly below 20 cm. The similar water perching was also observed in the cross-section 40 and 60 cm. The dye flow pattern did not appear to be linked to rock fragment content of each layer, probably because dye dispersal varied across the three dimensions of width, depth, and length.

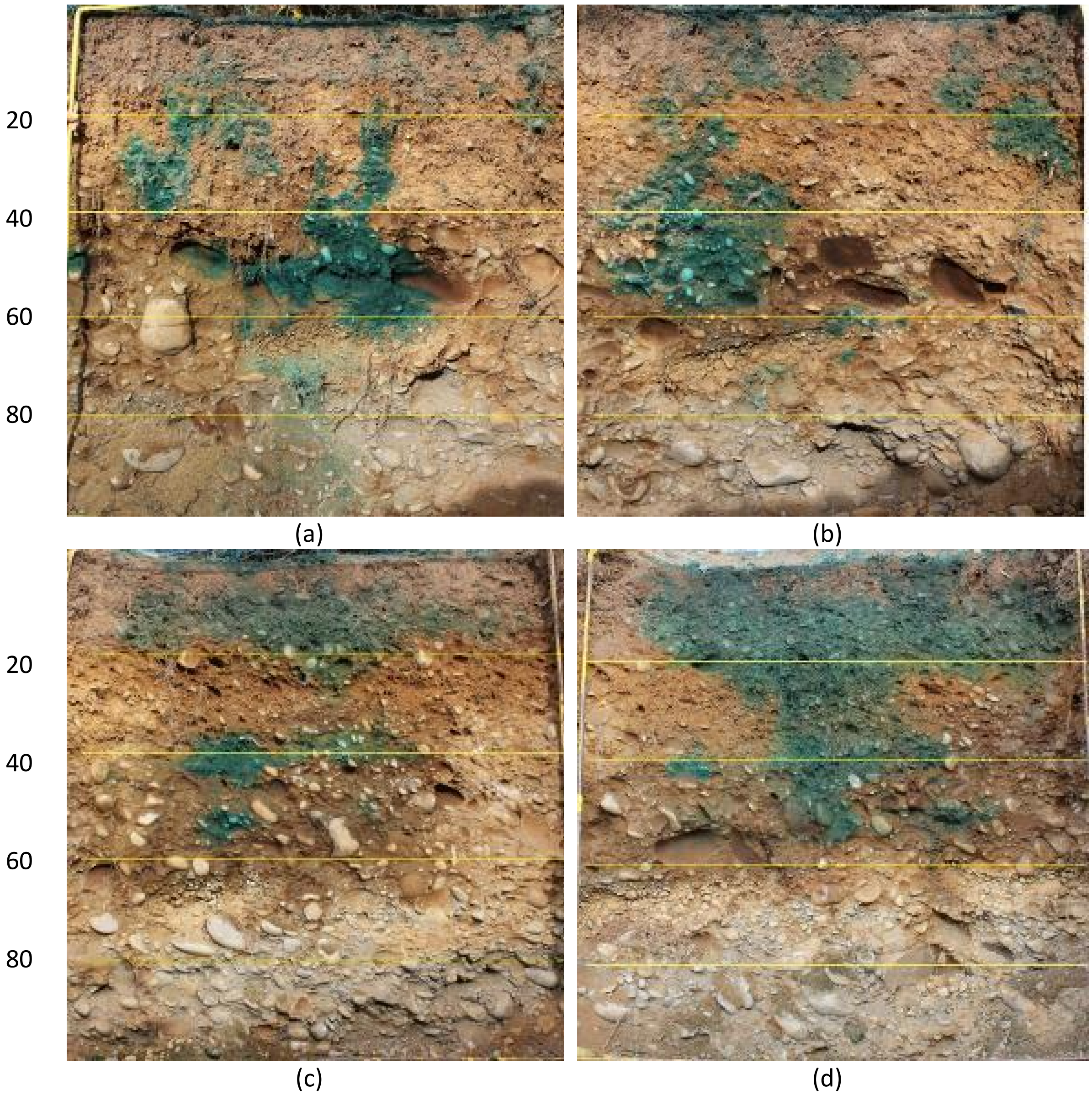


Figure 3.7. Photographs of visualized water flows at Site 1. Each photograph shows vertical cross-section (a) 20 cm, (b) 40 cm, (c) 60 cm, and (d) 80 cm into the wall of the pit. Yellow lines mark depths by every 20 cm.

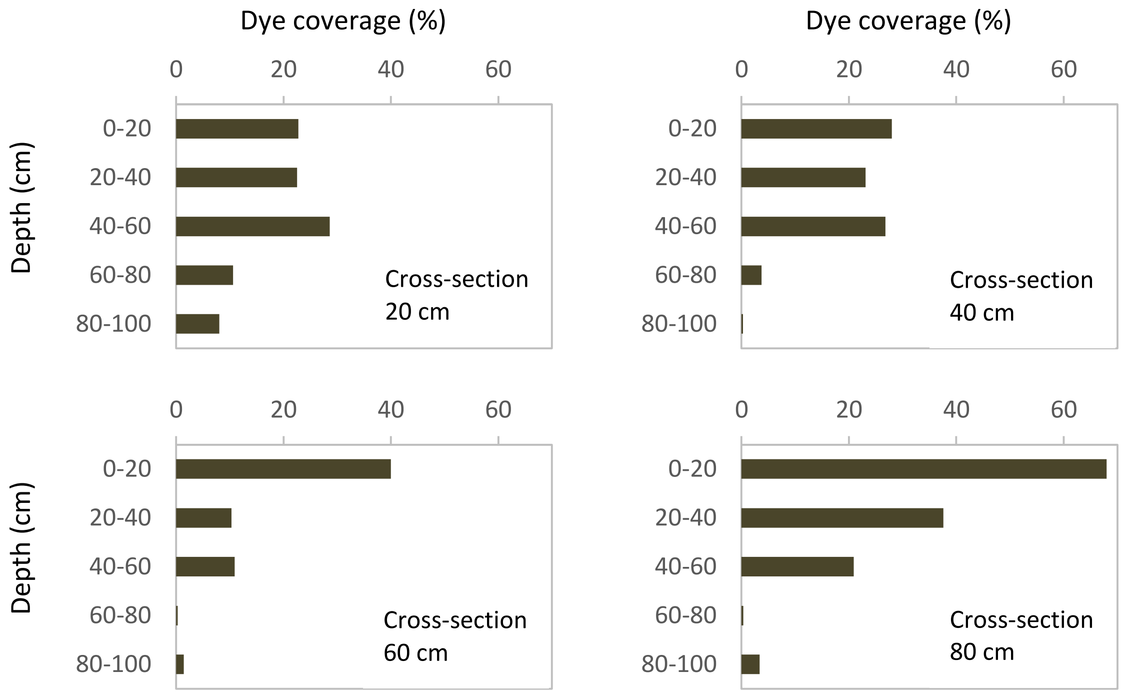
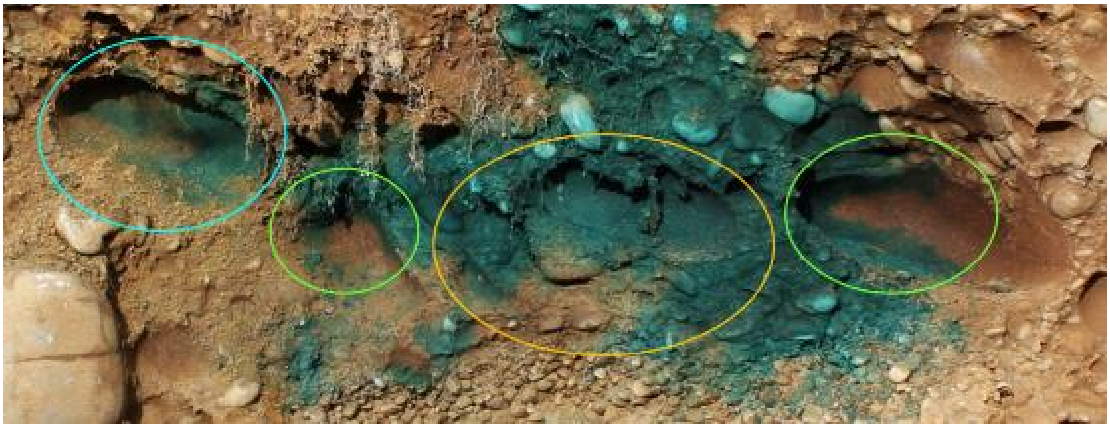


Figure 3.8. Dye coverage areas (%) by depth at cross-sections 20, 40, 60, and 80 cm at Site 1.

Figure 3.9 displays noticeable water movements around rock fragments in cross-section 20 and 40 cm. Coloured circles indicate different patterns of water flow generated by rock fragments. Yellow circles point out that soils, underneath hollowed spots where the rock fragments were positioned, were undyed while soils above, beside, and the further below the hollowed spots were dyed. It implies that the rock fragments interrupted downward water flows and made the water detour along their surface. This is supported again by evidence in green circles which showed the obvious water detouring. The green circle on the left indicates the vertical detouring, and the one on the right presented the horizontal detouring. On the other hand, a blue circle points an isolated stained area just at the hollowed spot, which implies the water preferably flowed through soils around the rock fragment. This demonstrates the rock fragment not only interrupt water flows but also enable to provide a preferential pathway for water. An interesting point is that a colour of dye in the blue circle was lighter than the dye in the yellow and green circles. Colour concentration of dye allows estimation of the mass of water. The clear and strong colour presents a heavy flow, and a light and faded colour presents a small and light flow. This means the flow in the blue circle was lighter than the other flows in the yellow and green circles. This implies the effect of rock fragment can be different depending on an amount of water flow. It seems that the rock fragment is an obstacle for heavy flows, but it is beneficial to light flows of water.

(a)



(b)

Figure 3.9. Water flows near rock fragments observed in cross-sections (a) 20 cm and (b) 40 cm. Yellow and green circles indicate disturbed water flows by the rock fragment whereas a blue circle points preferentially flowed water around the rock fragment.

Water flow at Site 2

Figure 3.10 shows movements of dye tracer at four cross-sections at Site 2. Again, a variation of rock fragment content was identified visually as the rock fragments were rarely found in a topsoil compared to the other layers, but the rock fragments were less concentrated at a deep soil layer. Generally, a colour of dye was light in all the cross-sections. Dye infiltration occurred through all the cross-sections; however, dye percolation at Site 2 was much shallower than Site 1. While dye coverages of 40-60 cm soil were 10-30 % at Site 1 (Figure 3.8), soils deeper than 40 cm at Site 2 presented no dye stain at cross-sections 20, 60, and 80 cm and only 5 % coverage at cross-section 40 cm (Figure 3.11). The most different feature of Site 2 from Site 1 was frequent cracks in the topsoil; They appeared in all the cross-sections but only in the topsoil. Mostly, the dye flowed along the cracks, which resulted in obvious preferential flows; Figure 3.12 shows clear crack flows generated in the cross-section 40 and 60 cm. There was a horizontal continuous crack at a depth of 20 cm, and the dye flowed out of the boundary of the cross sections through this crack, which seemed to limit downward water movements. This would be a reason for the low dye coverages in the deep soils.

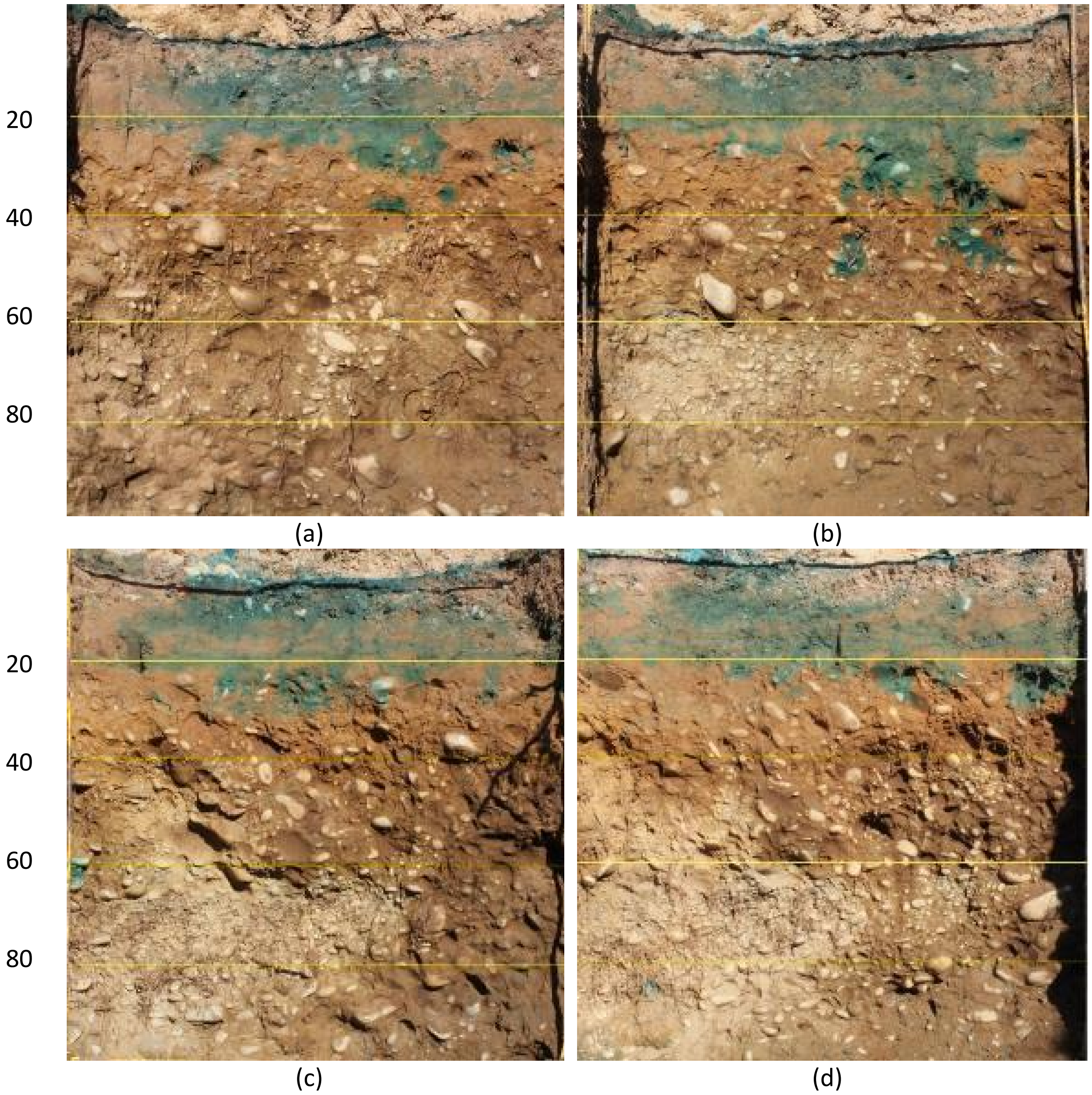


Figure 3.10. Photographs of visualized water flows at Site 2. Each photograph shows vertical cross-section (a) 20 cm, (b) 40 cm, (c) 60 cm, and (d) 80 cm into the wall of the pit. Yellow lines mark depths by every 20 cm.

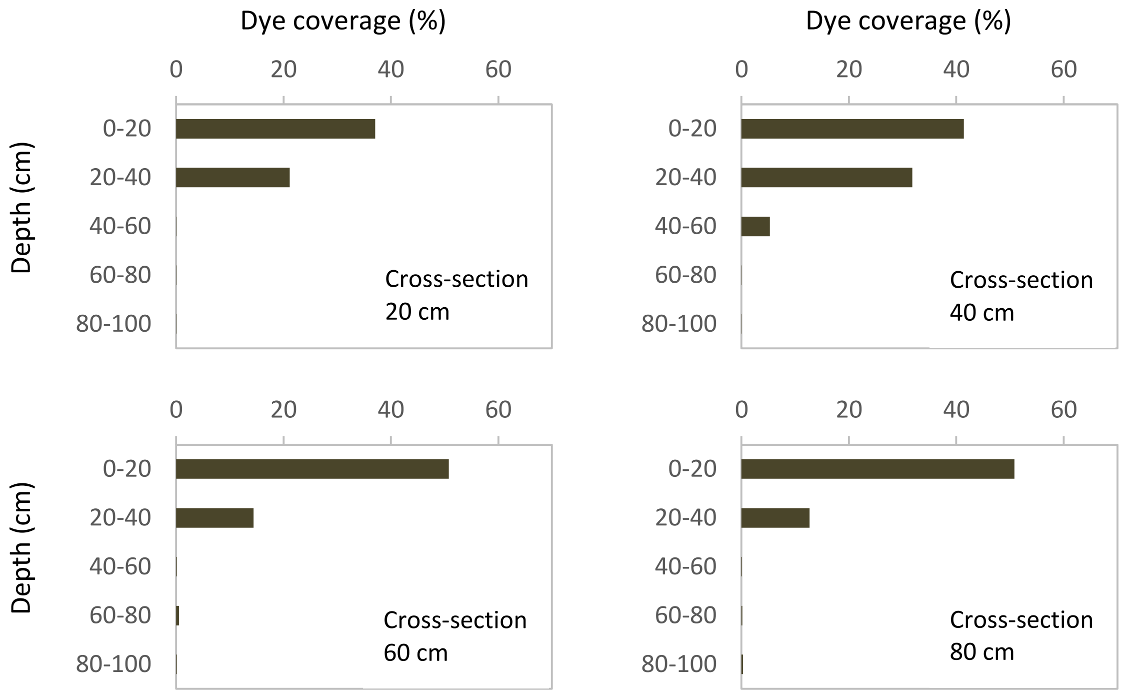


Figure 3.11. Dye coverage areas (%) by depth at cross-section 20, 40, 60, and 80 cm at Site 2.

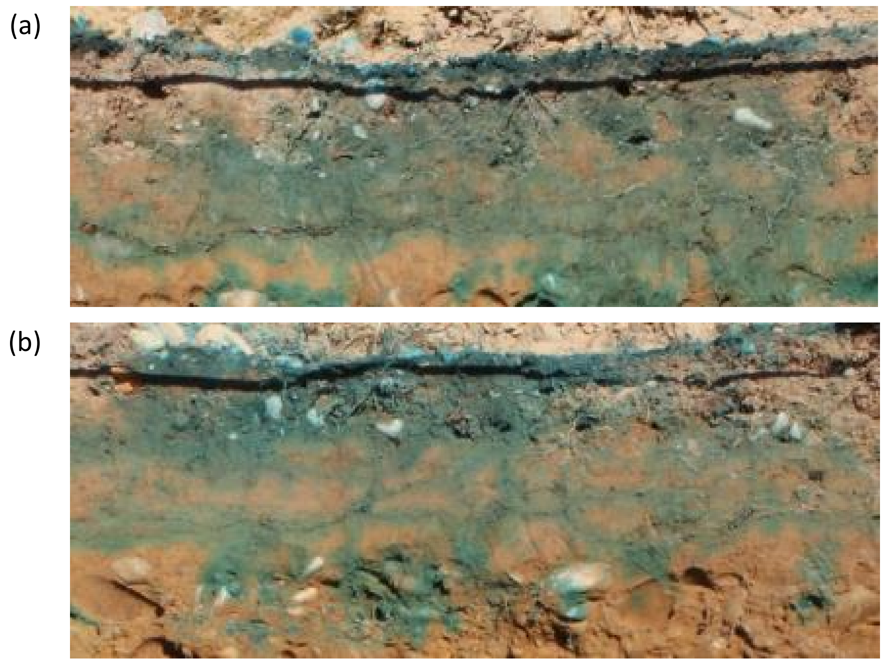


Figure 3.12. Dye flows through cracks in cross-section (a) 40 cm and (b) 60 cm.

Although the dye coverages deeper than 20 cm were very low, there was a local deep penetration of water in one part of the profile. Figure 3.13 presents several dye flows deeper than 20 cm in depth at Site 2. Blue circles indicate that the deeper dye percolation mostly occurred around hollowed spots where rock fragments were located. Figure 3.13a shows an isolated dye stain below the crack, and Figure 3.13b, c, and d present further downward water flows from the crack. Figure 3.13d clearly shows the downward water flow out of the crack generated only at the hollowed spots. This is a strong evidence that rock fragments provide preferable pathways for water as described in the result of Site 1.

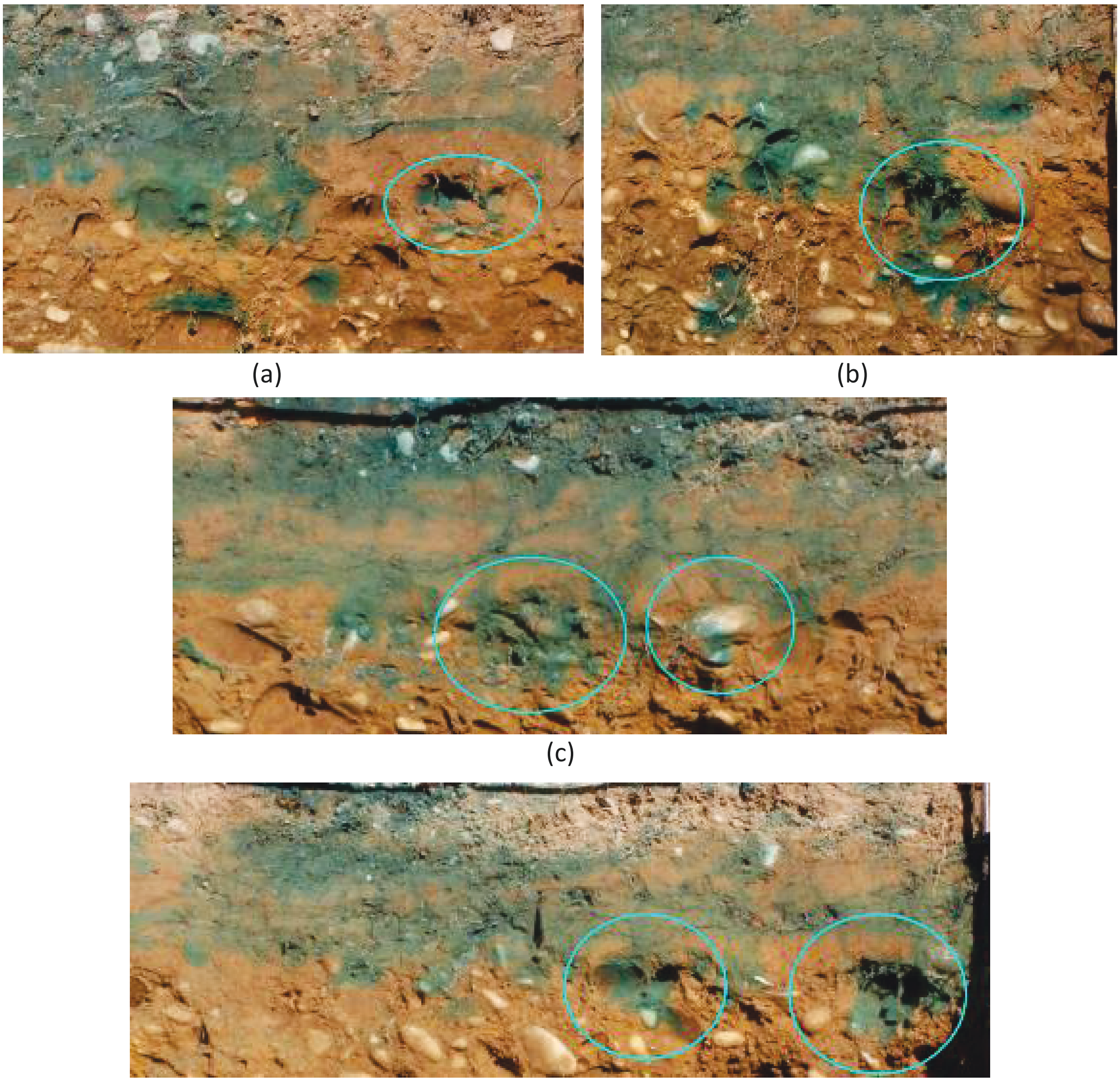

(a) (b) (c) (d)

Figure 3.13. Further downward water flow out of cracks around hollowed spot in cross-section (a) 20, (b) 40, (c) 60, and (d) 80 cm.

Water flow at Site3

Figure 3.14 shows visualized dye flows in cross-sections at Site 3. Different from the other sites, Site 3 did not have soil horizons which should be clearly differentiated by soil colour and texture. Although a variation of rock fragment contents by depth was the slightest on this site (Table 3.1), a distribution of rock fragments was considerably different by profiles; cross-section 20 cm looked the most stony and cross-section 80 cm looked the least stony. From this, soils at Site 3 seemed to be more disturbed by a land conversion than the other two sites. Plant roots were observed frequently through the whole cross-sections, even at bottom layers (Figure 3.14a and b), probably because pasture was nearby. Flow patterns at Site 3 were more similar to Site 2. Cracks were usually found in a topsoil and preferential flows occurred along the cracks. Not only the distribution of rock fragments but also the water flow patterns were highly different by the cross-sections. Major dye penetration was generated in cross-section 40 cm; dye coverages deeper than 40 cm soils appeared over 20 % only at the cross-section 40 cm (Figure 3.15). Differently, the dye coverages in the cross-section 80 cm were very low.

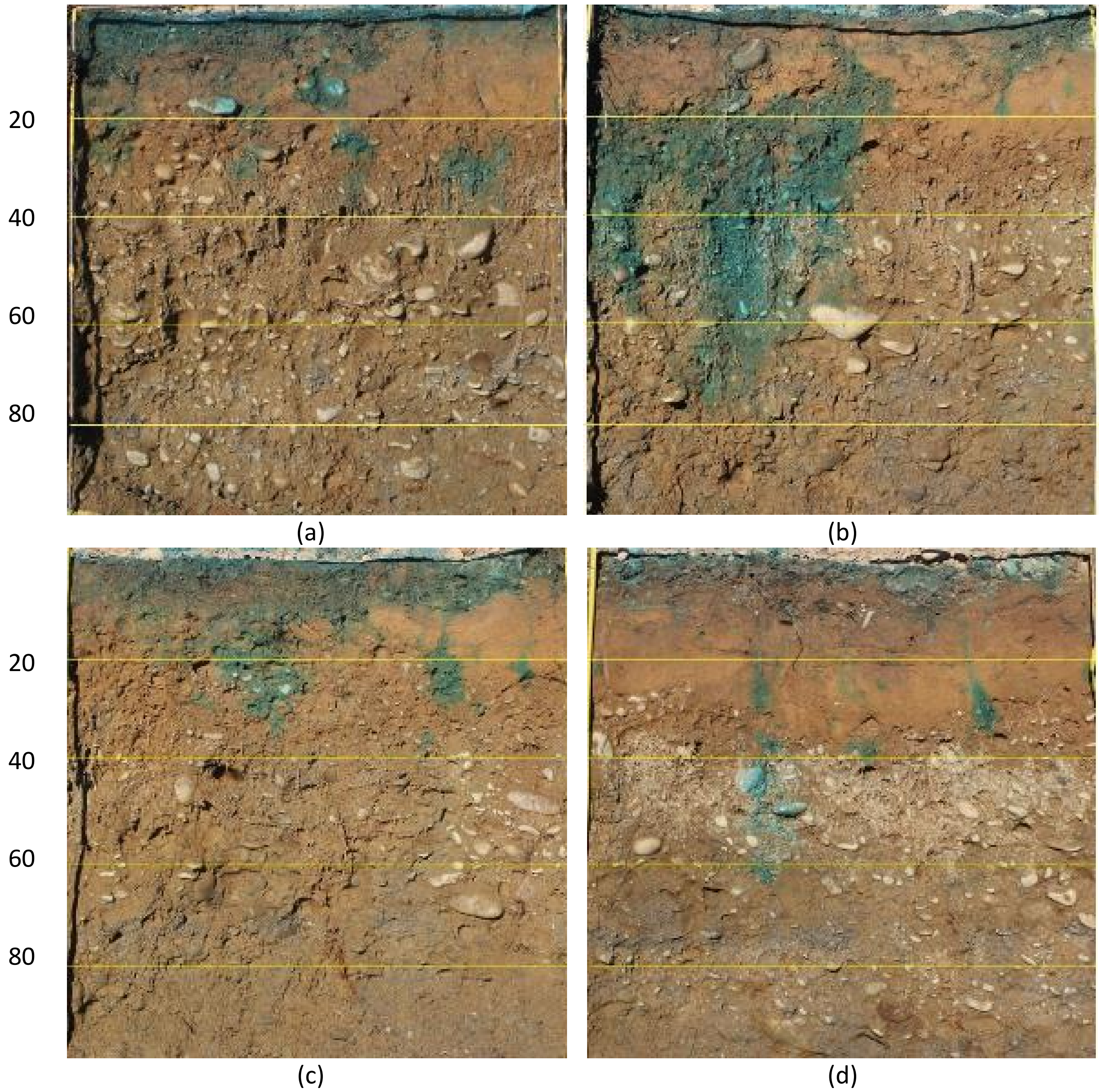


Figure 3.14. Photographs of visualized water flows at Site 3. Each photograph shows vertical cross-section (a) 20 cm, (b) 40 cm, (c) 60 cm, and (d) 80 cm into the wall of the pit. Yellow lines mark depths by every 20 cm.

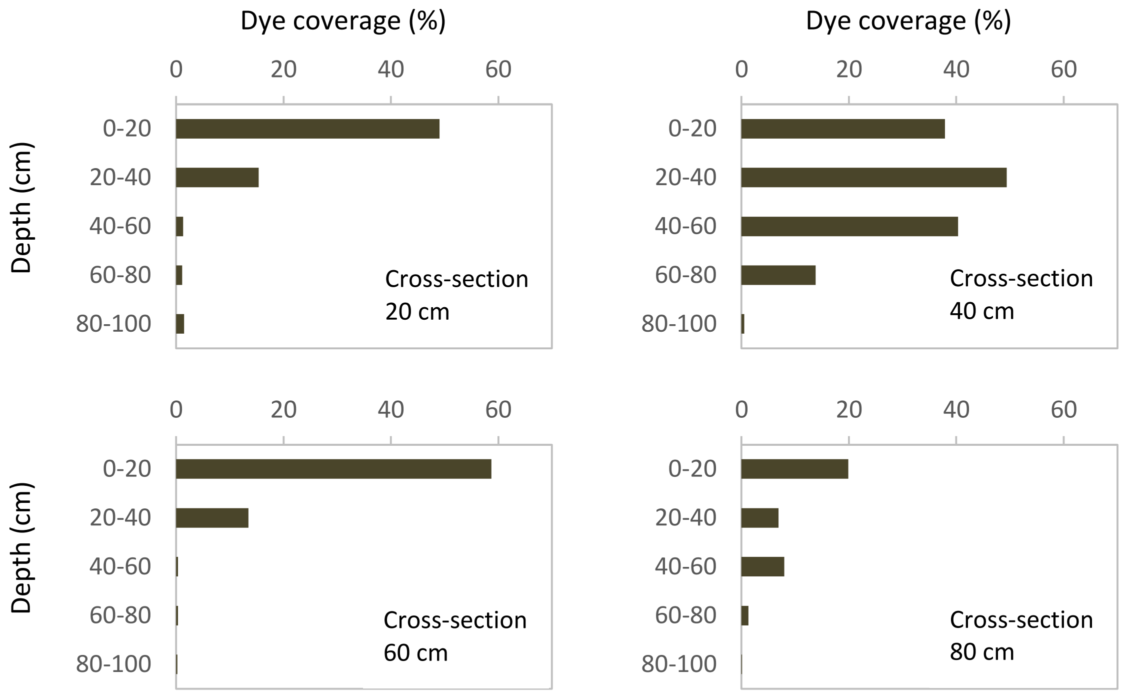


Figure 3.15. Dye coverage areas (%) by depth at cross-section 20, 40, 60, and 80 cm at Site 3.

One of the noticeable features at Site 3 was partial mineral soil zones. Figure 3.16 indicates the mineral soil zones in yellow boxes and rock fragment zones in green boxes. The mineral soils zone would be compacted in that bulk density of topsoil at Site 3 was relatively high (Table 3.4). Whereas rock fragments were more concentrated in deeper soils at Site 1 and 2, the rock fragments at Site 3 were more randomly concentrated through whole profiles. The random concentration of rock fragments obviously affected water flows. In Figure 3.16c, infiltrated dye stopped at a boundary of the mineral soil zone; few flows through the zone occurred by cracks. It seems that water did not preferably flow through the compacted mineral soil zone, which generates one-sided water flow in cross-section 40 cm (Figure 3.14b). Another interesting point is that plant roots only appeared where the rock fragments were located. No root was found in the yellow boxes, but the roots appeared in the green boxes. This implies the rock fragment was helpful to root penetration.

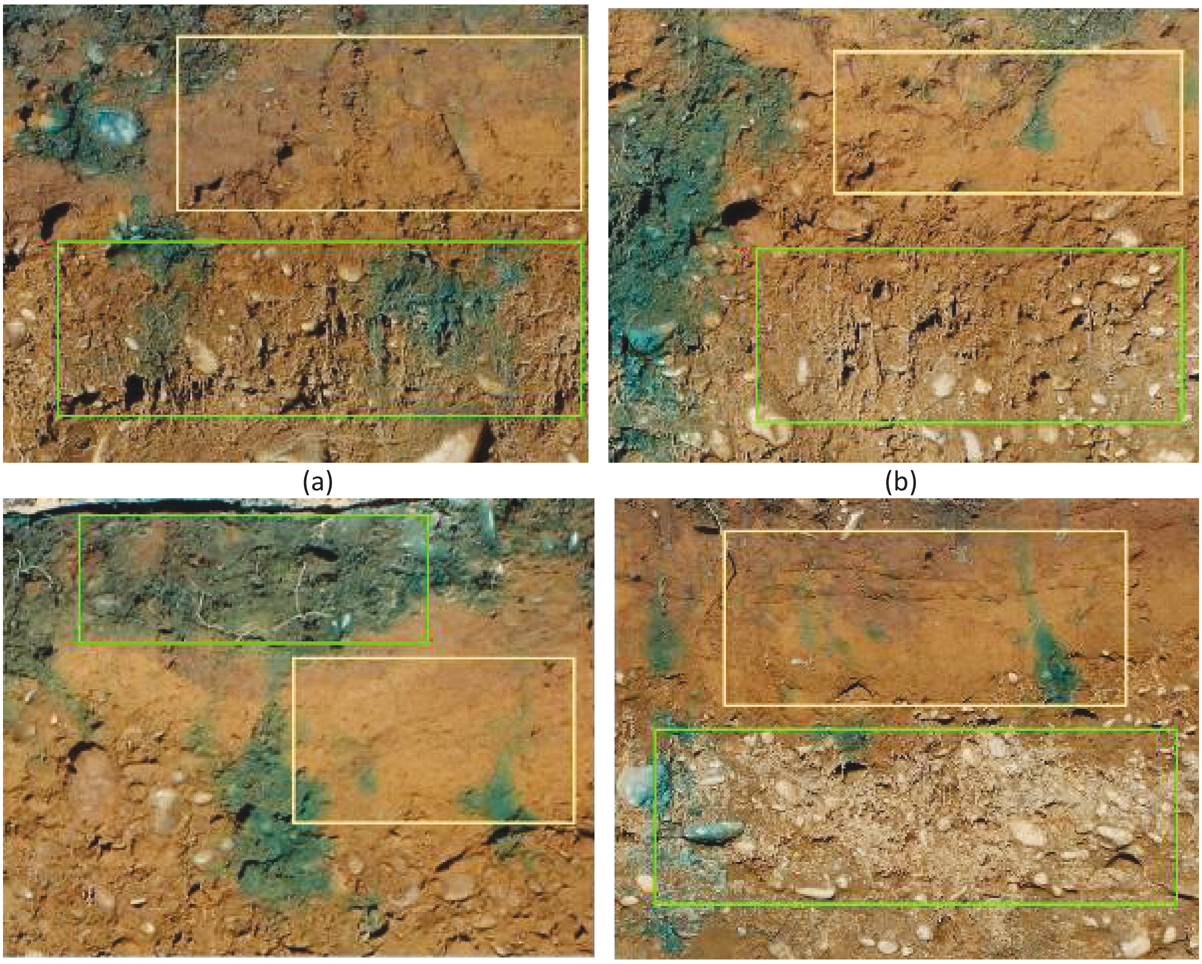


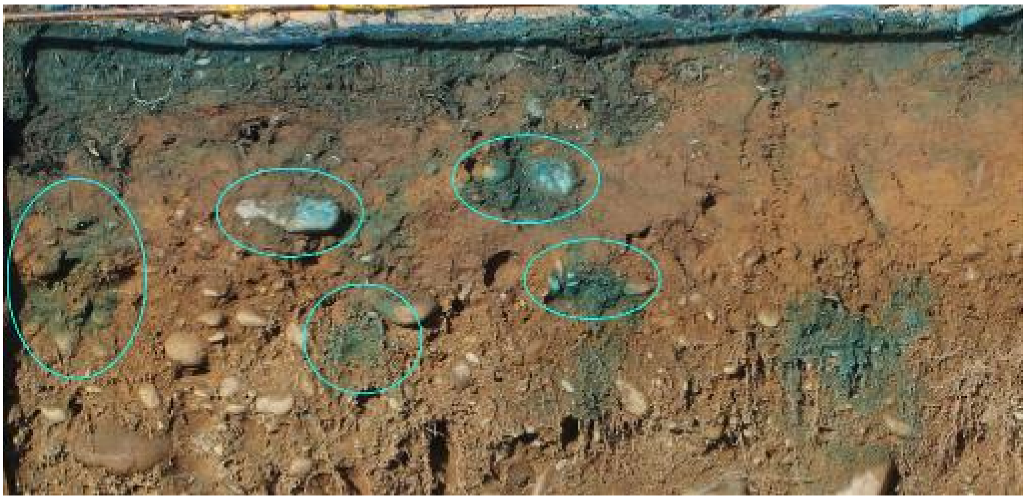
Figure 3.16. Mineral soil zones (yellow boxes) and rock fragment zones (green boxes) in cross-section (a) 20, (b) 40, (c) 60, and (d) 80 cm.

Yellow circles in Figure 3.17 point preferential dye flows from a soil surface to a subsoil in cross-section 40 cm. Infiltrated dyes flowed through a surface of rock fragments, cracks, and plant roots, which indicates they provided main pathways for water. While the preferential flow in the right yellow circle stopped at the end of the crack, the dye flow in the left and middle circles flowed continuously to deeper layers. Again, the dye was not likely to flow through compacted mineral soils at the end of the right yellow circle.

Site 3 also shows an evidence of positive effect of rock fragments on light water flows. Blue circles in Figure 3.18 shows local dye flows where the rock fragments existed. Encouraging effects of rock fragments on deeper water flows were observed more frequently, probably because Eyrewell soil was more likely to generate light flows.

Figure 3.17. Dye flows around rock fragments, cracks, and plant roots in cross-section 40 cm.

(a)



(b)

Figure 3.18. Dye flows along rock fragments in cross-section (a) 20 and (b) 60 cm.

3.4 Discussion

3.4.1 Noticeable features of Eyrewell soil related to water flow

Distribution of rock fragments

The three experimental sites contained a large amount of rock fragments, but distribution of rock fragments varied across the sites. Rock fragment content increased by depth at Site 1 and 2, but the increase was much larger at Site 1. In contrast, the rock fragment contents at Site 3 were evenly distributed by depth but they were randomly concentrated on one side. This heterogeneity, including the difference between the sites and a lack of uniformity in one site, seems to have been caused by earlier human disturbance, perhaps during forestry operations. Many previous studies have investigated the effect of land conversions on soil chemical properties, such as carbon dynamics and nitrogen cycles (Johnson et al., 1991; Morales-Romero et al., 2015; Rhoades & Coleman, 1999; Smith, 2008; Yanai et al., 2003), but studies on changes of soil physical structures are more limited. This is because the physical change varies, depending on the previous land uses, vegetation removal methods, and degree of disturbance. Site 1 shows distinct soil horizons by colours, a large amount of big stones and extremely compacted mineral soils in deep layers. Also, Site 1 was located near an original pine forest, so this site was likely to be the least disturbed among the three sites. In Site 3, which seemed to be the most disturbed, the land conversion significantly distributed the rock fragment from deep soils to upper soils. Processes of soil conversion usually include a mixing of A-horizon and subsoils (Kosmas et al., 2000), which destroys natural soil structures. Spatial heterogeneity of the current Eyrewell soil appears to be typical landscapes the whole of the converted area. Because the soil structure has a strong impact on soil water movement and retention (Bronick & Lal, 2005), the change in the location of rock fragments is addressed in later parts of this study, and effects of rock fragment contents on soil hydrology are further explored.

Frequent soil cracking in topsoil

Cracks were one of the noticeable features in Eyrewell soil, which were a dominant factor of preferential flow. Mechanisms underlying soil cracking are still not fully explored (Gargiulo et al., 2015), but land conversion seems to influence on a crack development in Eyrewell, in the same way anthropogenic actions have been reported previously to generate soil cracks (Øygarden et al. , 1997). In this study, the cracks were not observed at Site 1 where would be the least disturbed, so this supports the relationship between the land conversion and soil cracking. The crack development is significantly related to shrink-swell phases and compaction of mineral soils (Bandyopadhyay et al., 2003; Spoor et al., 2003). During the conversion, topsoil would be more compacted by bulldozers or excavators, and repeated rainy and dry seasons in this area would trigger shrinkage and swell (Tang et al., 2008), which generated the cracks. Cracks have a huge impact on hydrological processes, air flows, and the diffusion of contaminants (Bandyopadhyay et al., 2003; Tang et al., 2008). The crack in this area is widely generated in the converted dairy pasture where a high amount of irrigation and fertiliser applies. Thus, the influence of cracks should not be neglected in future studies related to efficient water uses, nutrient loss, or pollutant distribution in Eyrewell.

Plant roots around rock fragments

Plant roots in Eyrewell soil tended to appear where rock fragments were positioned. This observation is consistent with the study of Rytter (2012); root density was much higher near the rock fragments which suggests that the rock fragments were beneficial for root growth. Although there is a debate on a role of rock fragments in a plant growth (Qin et al., 2015), rock fragments have been reported to improve the root growth in compacted soils; usually, high levels of soil compaction is a negative factor for the root growth (Chen & Weil, 2010), but the rock fragments in subsoil provide the more profitable physical condition for the root development (Estrada-Medina et al., 2013). Also, the rock fragments reduce bulk density of mineral soil, which make root penetration easier (van Wesemael et al., 1995). Moreover, a fertiliser is more concentrated in mineral soils with the existence of rock fragments because increasing rock fragments decreases mineral soils but mostly not influence the amount of input (Poesen & Lavee, 1994). Preferential flows generated by rock fragments also contribute to accumulating nutrients in flow paths (Rytter, 2012). Plant roots would be attracted by this nutrient pool, and thus, they tend to grow towards rock fragments.

3.4.2 Water flow patterns in Eyrewell

Dominant crack flows

Preferential flows occurred at all of the experimental sites. There were several factors that generated preferential flows, such as cracks, varied rock fragment contents, and plant root channels, but the flows through the crack were the dominant patterns. Crack flow refers to continuous preferential flows following cracks (Blake et al., 1973). In this study, the cracks usually appeared in topsoil, and one of the cracks was continued horizontally at the depth of 20 cm, limiting downward water movements. Rapid crack flows in topsoil enables to protect a surface of soils from erosion by increasing infiltration and decreasing runoff (Mason et al., 1999). However, infiltrated water bypasses most of the soil, so the water cannot be efficiently used by plants (Dobrovolskaya et al., 2014). In addition, preferential water flows do not allow nutrients to have enough time to contact with soils for ion exchanges, so the only minor amount of nutrients can be retained in soils (Mason et al., 1999). According to Toor et al. (2004), land use changes into dairy farms have been increased an application of fertiliser to maintain proper levels of pasture production, and nutrient losses increased when a nutrient application exceeded a capacity of the soil. Under crack flows, water can contact to soils only around cracks, so the nutrient loss would occur once the soils around cracks are saturated with nutrients although the rest of the soil still enables to hold more nutrients. Soils in preferential flow paths have better nutrient supplies than the rest of the soil (Bundt, Jäggi, et al., 2001), but whole nutrient levels in the soil would decrease. Because cracks would generally exist in a converted area in Eyrewell, there is a high possibility of inefficient fertilizer uses and groundwater pollution. This is not only a serious economic loss for farmers but also a severe concern for the environment. The Canterbury soil was already reported to leach a large amount of phosphorus into the groundwater, which was applied to grow dairy pasture (Toor et al., 2004). High stoniness of Eyrewell soil is generally known to result in free-draining, but cracks seem to be another significant factor for the rapid water movement. Moreover, the impact of cracks was more dominant in an initial water movement in the topsoil than the effect of rock fragments.

Water perching at the boundary of soil layer

Water perching was observed at a boundary of soil layers at Site 1. The water perching was not a major flow pattern in experimental sites, but this phenomenon needs to be addressed because it could occur where there is no crack. Infiltration at Site 1 flowed regularly without bypassing (Figure 3.7d), however, when the water reached at a depth of 20 cm, the water flowed only through the middle of the soil. This phenomenon was likely to be caused by a variation in soil properties, especially soil texture. A topsoil in site 1 was loam while an underlying soil was sandy loam which included 15 % more sand than the topsoil. Previously, Dobrovolskaya et al. (2014) demonstrated a water flow in a layered soil with a finer textured soil overlying a coarser soil. Water flowed regularly through the finer soil but started being irregular after passing an interface between the layers. Textural heterogeneity in a soil profile with finer soils overlying coarser soils has an influence on soil hydrology by enhancing water storage and plant available water in the finer soil (Huang et al., 2013; Zettl et al., 2011). Power of holding water in the finer soil is mostly derived from capillary barrier. Figure 3.19 illustrates the capillary barrier generated in an interface of layered soils. Capillary force of the fine soil restricts downward water movements, which increases saturation of the finer soil until the capillary barrier is broken (Mancarella & Simeone, 2012). Even slight textural difference, for example, fine sands and coarse sands, can significantly increase the water storage in the finer soil (Dobrovolskaya et al., 2014). Eventually, a layered soil system is more vulnerable to preferential flow (Dobrovolskaya et al., 2014), but the textural heterogeneity would be helpful to increase water storage in Eyrewell topsoil.

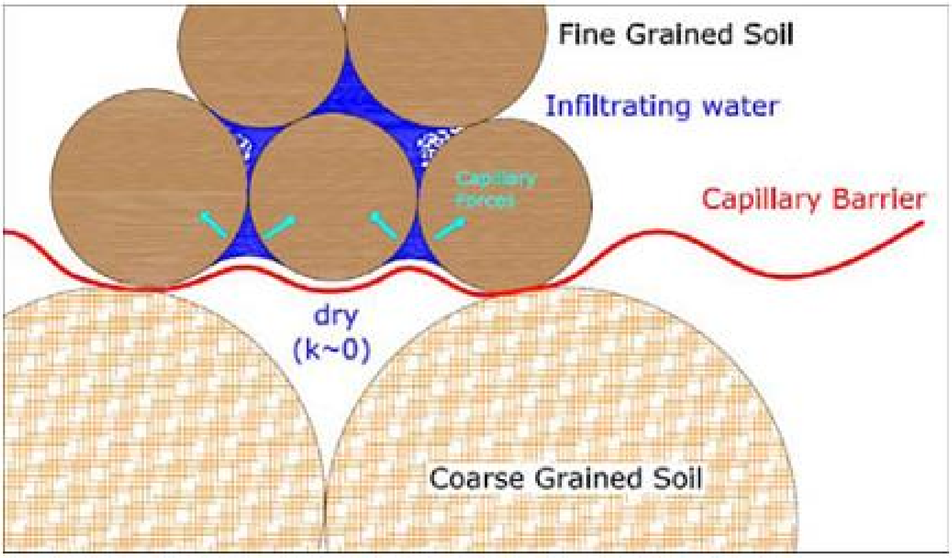


Figure 3.19. Capillary barrier in a textural layered soil (Mancarella & Simeone, 2012).

3.4.3 Effects of rock fragments on water flow

Rock fragments were not the most influential factor on water flows in Eyrewell. There was no evidence that the rock fragment determined overall water movements at the experimental sites. There was no continuous flow along a surface of rock fragments, and there was no change in a major direction of water movements due to rock fragments. However, the rock fragments located on the way of flow paths still have a noticeable influence on the water movement.

Dye concentration and water flow

Colour concentration of dyed areas allows to estimating a character of water flow. A vivid colour implies that a high volume of water flows through limited space. The dye did not disperse to the adjacent soil, which implies the flow was fast and had no time to be spread out from preferential pathways (Alaoui & Goetz, 2008). On the contrary, a faded light colour of dye implies that the water flow is a small volume or widely-spread. This flow would be slow so the water could be dispersed to the adjacent soil. This implies soil moisture at lightly dyed areas is lower than heavily dyed areas.

Influence of rock fragments on heavy water flow

Heavy water flow refers to a clear and strong colour of dyes in the present study. It was observed that rock fragments interfered with heavy water flow both horizontally and vertically (see Figure 3.9). When the heavy flow encountered the rock fragments, it had to detour a surface of them, remaining soils beneath the rock fragments dry. Obviously, the rock fragments increased tortuosity, which is one of the main effects of rock fragments (Mehuys et al., 1975). The detouring would make a water path more complicated as illustrated in Figure 3.20. Compared to Figure 3.20a, the water paths in Figure 3.20b is more diverse due to the rock fragments, and eventually, the water is dispersed more extensively. This effect would be larger if a size of rock fragment is larger. In addition, the increased tortuosity can slow down flow rates and delay leaching. Heavy flows transport a high amount of water and nutrient. The effect of rock fragments on reducing the flow rates would positively affect water and nutrient efficiency because delayed water movements increase water resident time in soils, thus, water conservation would increase (Novák & Šurda, 2010). This implies the rock fragment in Eyrewell, particularly situated on the way of heavy flows, can be beneficial to the efficient use of water and fertiliser, and decreases environmental concerns. Previously, Tetegan et al. (2015) insisted an assumption that rock fragments hinder an ecological function of soils should be reconsidered because the rock fragments acted as a water reservoir in their research. In the present study, water retention or soil moisture were not measured, however, a possibility of the positive contribution of rock fragments is identified.

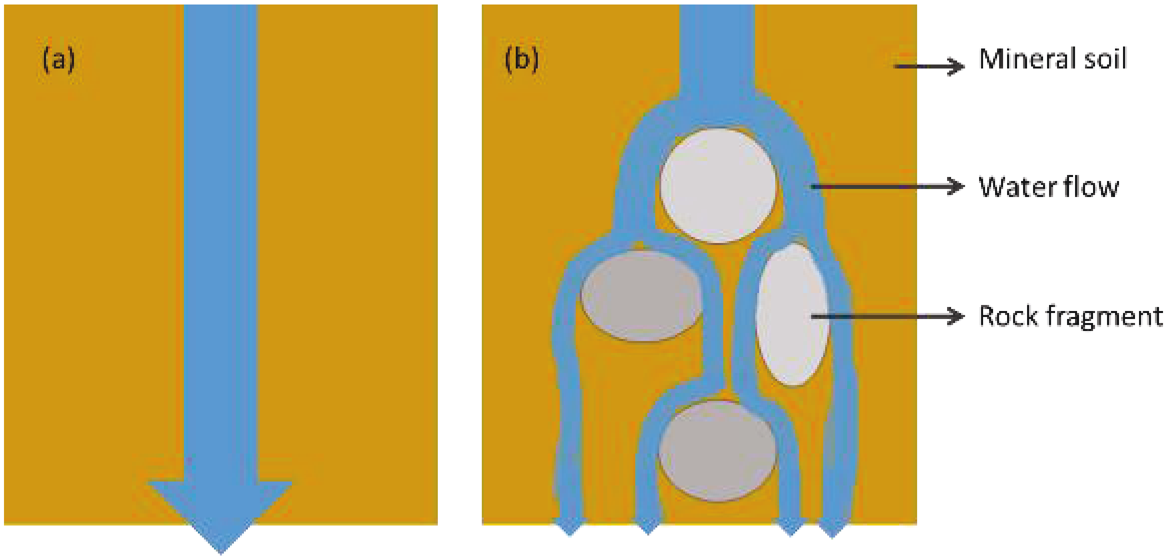


Figure 3.20. Illustration of heavy preferential water flows through (a) a mineral soil and (b) soil with rock fragments. The straightforward preferential flow is interrupted by rock fragments, and accordingly, water is more distributed.

Influence on light water flow

Light flow refers to a relatively light and faded colour of dyes in the present study. Rock fragments provided preferable pathways for light water flows. This effect was distinctly observed around cracks (Figure 3.13). Mostly, water tended to flow along the cracks, but the water flowed out of the cracks with the presence of rock fragments, which resulted in local deep penetration in one part of the profile. In addition, isolated dye stains appeared where the rock fragments were positioned (Figure 3.18), which also supports soil-rock interfaces provided the preferential paths for the light flow. This result is similar to the previous studies that rock fragments generated preferential flows (Sohrt et al., 2014; Su, 2001), which is because of the bigger pores around rock fragments (Cerdà, 2001). In a general viewpoint, preferential flow is not beneficial for the environment because a large amount of water and nutrient bypasses most parts of soils (Dobrovolskaya et al., 2014). However, in Eyrewell, preferential flows seem to be advantageous to distribute water more broadly. When most waters flowed through the cracks, the rock fragments broke crack flows and provided another pathway, eventually, the rock fragments contributed to increasing dye coverage areas in soil profiles.

3.4.4 Effects of plant roots on soil hydrology

Rock fragments are able to affect water flows indirectly by changing root penetration. Dye flows along plant roots were not clearly observed in the present study, probably because the roots of a sparse ground cover of herbaceous wayside plants did not appear frequently in the study sites. In addition, the roots were mostly located near rock fragments, so it was hard to distinguish the effect of plant roots from that of rock fragments. However, many other research projects have proved that plant roots create preferential pathways (Devitt & Smith, 2002; Johnson & Lehmann, 2006; Schwärzel et al., 2012) and changed soil pore structures, which could alter water flow patterns (Ma et al., 2010). Also, substances exuded or formed by plant roots, such as mucilage, polymeric materials, and assimilated carbon, have reported to influence water dynamics near the roots and soil-root interfaces (Carminati et al., 2011; Gregory, 2006). In the presence of rock fragments, rock-soil-root interfaces can either promote or interfere water flows (Zhang et al., 2016). There are limited studies on soil hydraulic processes between rock fragments and plant roots, and field research remains infrequent, therefore, a future investigation is necessary to determine a combination effect of rock fragments and plant roots on water flow (do Carmo et al., 2016).

3.4.5 Importance of initial soil moisture

It was assumed in the present study that initially low soil moisture before dye application (no rainfall for at least a week) would provide the best starting conditions. However, initial soil moisture has been shown to be a critical factor to determine thickness of dye flow and depth of dye penetration in the research of Weiler and Flühler (2004). On the contrary, Flury and Flühler (1994b) reported initial soil water content had no clear effect on flow patterns but irrigation methods, such as sprinkling and flooding, induced differences. Thus, future research is required to identify changes of flow patterns with different irrigation methods under various initial soil moisture condition.

3.5 Conclusion

Recently, Te Whenua Hou has been converted from a pine forest to a dairy farm, with ecological restoration on set-aside reserves and farm margins. In spite of the importance of soil and water for the converted areas, there have been limited studies on these topics since the conversion. The present study investigated soil characteristics and water flow patterns in the converted area and effects of rock fragments on water flow in three experimental sites, which have led to the following conclusions:

Ⅰ. Cracks which generally appeared in topsoil of the converted area were the most influential factor for topsoil hydrology. Cracks were major preferential pathways, and a horizontal crack was likely to interrupt further deep penetration of water. Frequent crack flows would be a concern to reduce efficiency of water and fertiliser and increase groundwater pollution.

Ⅱ. Horizontal and vertical spatial distribution of rock fragments was greatly uneven across the site. This heterogeneity would induce different spatial water flow patterns, and future study should consider this as an important characteristic of converted Eyrewell soil.

Ⅲ. Rock fragments are likely to have a positive effect on increasing water use efficiency in Eyrewell soil. Water detouring along a surface of rock fragments interrupted straightforward leaching of water and distributed water more broadly, which eventually increased water residence time in soil. Also, rock-to-soil interfaces provided another flow pathway besides cracks, which increased water-soil contact areas. The result of this study suggests the rock fragments in Eyrewell can be beneficial to soil water, contrary to general assumptions that rock fragments enhance free-drainage.

Ⅳ. The presence of rock fragments was favourable for plant root penetration. Although the direct influence of plant roots on water flow was not observed in the present study, plant roots have been reported to have an important influence on soil water dynamics. Thus, the combined effect of rock fragments and plant roots is worthy of further investigation.

Ⅴ. The work described in the present chapter has provided an overview of the current status of Eyrewell, as a step towards devising a prescription for Eyrewell soil in the wider study.

Chapter 4

Effect of rock fragment contents and sizes on soil hydraulic properties in repacked soil columns

4.1 Introduction

Soil hydraulic properties are very important for efficient water management. They enable estimation of water holding capacity and solute transports, which have a huge influence on the environment. Saturated hydraulic conductivity (K_{sat}) is a key parameter in the context of irrigation, drainage, water movements, and solute transports in soil (Abdelbaki, 2015). This is a measure of the ability of soil to move water through its pore spaces when saturated; K_{sat} is calculated as a proportional constant from Darcy's law in which the quantity of water is proportional to the cross-sectional area of soil columns and hydraulic gradient, but inversely proportional to the length of the soil column. Naturally, this value is closely related to pore systems of the soil. Pores are the main pathways of water movement, and their sizes are critical to determining soil hydraulic characteristics as (Sakaki & Smits, 2015). Different pore size classes can be measured by a tension infiltrometer (Bodhinayake et al., 2004) which estimates the relative importance of different sized pores by different pressure heads (Li et al., 2008; Wilson & Luxmoore, 1988).

The effect of rock fragments on soil hydraulic properties is far from clear. Novák et al. (2011) reported saturated hydraulic conductivity decreased with increased rock fragment content, but contrary to this, Beckers et al. (2016) found an increase in water flow with increasing rock fragment content. Not only rock fragment content, but also sizes, positions and shapes of rock fragments influence on soil hydraulic processes (Zhang et al., 2016). In particular, the size of rock fragments has a stronger impact on water flow than the other characteristics (Mukhlisin & Naam, 2015). However, studies of rock fragment sizes have also shown conflicting results. According to Shi et al. (2012), smaller rock fragments had more impact on decreasing infiltration than larger rock fragments. Katra et al. (2008) also found that larger rock fragments enhanced soil water retention and absorption. However, Guo et al. (2010) reported that rock fragment sizes did not show any significant difference in runoff rates.

Repacked soil columns have been commonly used to study stony soil to provide homogeneous soil conditions without soil layers, earthworm burrows, and decayed root holes, which allows for repetitive and reproducible study (Lewis & Sjöstrom, 2010). Thus, by using repacked soils, the sole-effect of rock fragments on soil water flow can be explored without being affected by those other factors. The aim of the work presented in this chapter was to identify the effect of rock fragment content and sizes on K_{sat} and tension infiltration rates in repacked soil columns, using Eyrewell soils.

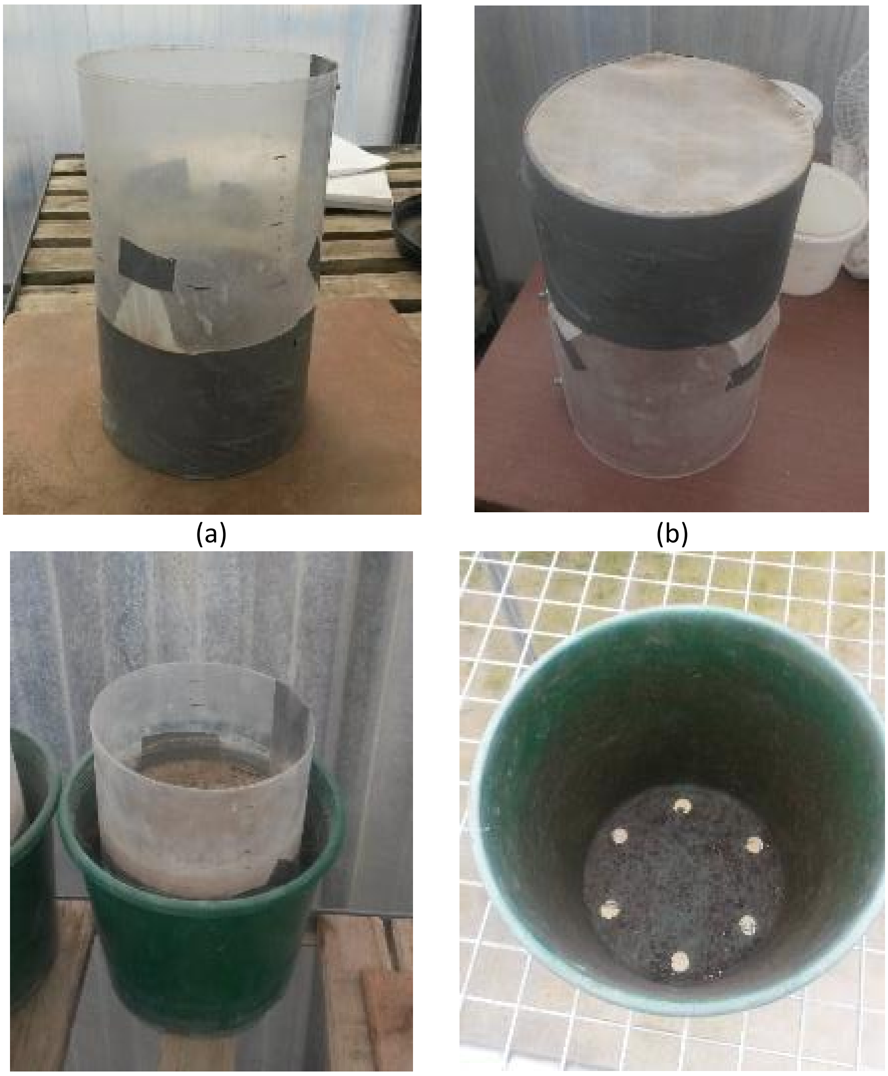
4.2 Materials and Methods

4.2.1 Soil sample collection and preparation

Soil samples were collected near Site 1 (see Chapter 3.2.1). After creating the pit, the excavated soils including rock fragments were collected in bags using a shovel. Several stones larger than 15 cm in diameter were not collected because they were not suitable for use at a laboratory scale. The collected soil samples were moved to a laboratory and sieved as described in Chapter 3.2.4.

4.2.2 Column-making

Small columns (30 cm tall and 19 cm diameters) were constructed. Flat transparent plastic (thickness 1 mm) was rolled, overlapping both ends by 3 cm, fixed with bolts and nuts. Heads of the bolts were positioned inside the plastic column, so most of the bolt was outside of the column to minimize any interruption to water flow. The overlapping part was sealed with a waterproof tape to prevent leakage. A piece of net curtain covered a bottom of the column and was secured using waterproof tape, allowing water to pass but reducing a loss of mineral soil. Height was marked on the columns at 1 cm intervals. Figure 4.1a and b show a completed form of the column. The column was seated in a plastic pot for support and to protect the net curtain from being damaged by the heavy repacked soil (Figure 4.1c). The bottom of the pot had holes so water still enabled to be drained through the holes (Figure 4.1d).



(a) (b) (c) (d)

Figure 4.1. Experimental columns; (a) a completed plastic column with marked depth gradations, (b) a view of the column covered by a net curtain from below, (c) the column with repacked soil (17.7 cm in height and 5 L in volume) seated in a pot, and (d) holes at a bottom of the pot.

4.2.3 Soil repacking processes

The plastic columns were packed with different ratios of mineral soils, gravels, and stones. A weight of each fraction was measured using a balance and their volume was estimated by calculation, as described in Chapter 3.2.4. Packing was carried out by 5 cm depths to ensure the uniform distribution of the rock fragments. Mineral soils and rock fragments were weighed for each 5 cm layer, mixed in a container, and moved into the columns. The air dried soils were shaken to fill large gaps between particles, but there was no artificial pressure to the soils. The surface of the repacked soil was flattened by hand. Bulk density of the mineral soil in each column was between 1.7 and 1.8 g cm^{-3}. The repacked soil was 17.7 cm in height and 5 L in volume.

4.2.4 Treatments

There were nine component ratios of the repacked soils (Table 4.1). The treatments were in three groups with different stone content. The same group of treatments had the same stone contents but different gravel and mineral soil contents. The code for each treatment shows its stone and gravel content. 'S' refers to stone, 'G' refers to gravel, and the following numbers after the letters are percentages. The maximum stone content (40 %) was decided based on the field examination (Table 3.1), and the other ratios were decided to achieve a gradual increase.

Table 4.1. Nine treatments composed by different ratios of stones, gravels and mineral soils. The component ratios are volumetric contents.

Treatment	Total rock fragment content (%)	Component ratio		
		Stone (%)	Gravel (%)	Mineral soil (%)
S0G0	0	0	0	100
S0G17	17	0	17	83
S0G35	35	0	35	65
S20G0	20	20	0	80
S20G14	34	20	14	66
S20G28	48	20	28	52
S40G0	40	40	0	60
S40G10	50	40	10	50
S40G20	60	40	20	40

4.2.5 Soil texture and organic matter content

Table 4.2 shows texture, particle size distribution, and organic matter content of the mineral soil used for this study. Analytical methods were described in Chapter 3.2.5 and 3.2.7.

Table 4.2. Properties of mineral soil.

Texture	Particle size distribution (%)			Soil organic matter (%)
	Clay	Sand	Silt	
Sand	2.16	89.78	8.07	1.69

4.2.6 K_{sat} measurement

The repacked soil columns were placed in water to be saturated from the bottom (Figure 4.2a). When water ponding appeared at a surface, the soil was considered to be completely saturated. After this time (approximately 2 hours), water was added to the surface using a fine sprinkle to avoid disturbing the soil, to provide a 3 cm constant water head (Figure 4.2b). To keep the constant water head, water was added manually continuously. Leachate was collected in a bucket every 5 minutes (Figure 4.2c), measured using a balance. When the volume of leachate was the same three times, water flow was assumed to be stable. The leachate collection then stopped. K_{sat} was calculated using the equation of Darcy.

$$q = -\mathrm{ksat}\frac{A \triangle P}{L}$$

Where, q is the velocity of water flux per unit cross-sectional area ($cm^3\ min^{-1}$); k_{sat} is the saturated hydraulic conductivity; A is the unit area of the soil column (cm^2); $\triangle$P is hydrostatic pressure difference; L is the length of the soil column. Because the mineral soil and the rock fragment were packed homogeneously, the soils were considered to satisfy assumptions of Darcy's law (Beckers et al., 2016; Beibei et al., 2009).

(a)

(b)

(c)

Figure 4.2. K_{sat} measurement procedures; (a) soil column saturation, (b) a 3 cm constant water head, and (c) leachate collection.

4.2.7 Tension infiltration measurements

Two tension infiltrometers (Figure 4.3) were used to measure infiltration rates under different tensions. The tension infiltrometer consists of a base disc (10 cm in diameter), a main tube, and a tension tube. A bottom surface of the base disc is covered with a membrane which allows water to pass by matric potential. When the membrane touches soil surfaces, soil pores start pulling water in the main tube. The tension tube gives a holding power to the infiltrometer. When there is no water in the tension tube, the water in the main tube is free to infiltrate into soils. However, when there is water in the tension tube, the infiltrometer can hold the water. Different levels of holding power can be applied by adjusting a water head in the tension tube. When the water head is higher, the holding power is stronger. Water movement from an infiltrometer to the soil is determined by the gradient between a pulling force of soil pores and a holding power of the infiltrometer. If the pulling force of the pore is the same or stronger than the holding power, water in the main tube would flow into the soil. In contrast, if the pulling force is not strong enough, the water would stay in the main tube. The finer pores have stronger matric force than the larger pores, so the tension infiltrometer can measure the quantity of different sized pores by giving different tensions.

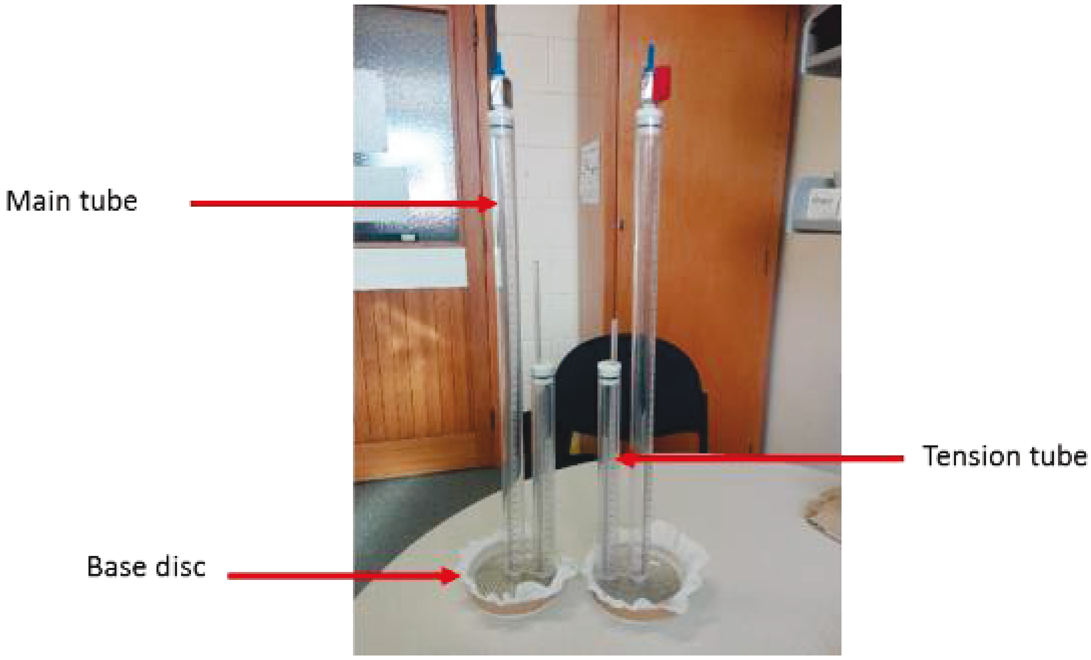


Figure 4.3. Tension infiltrometers used in this study.

Four tensions (13, 10, 6, and 3 cm of water heads) were used in this study. Each tension was equivalent to the matric potential of -1.47, -1.17, -0.77 and -0.47 kpa because of the space (1.7 cm) between the bottom surface of the base disc and the end of the tension tube. Table 4.3 shows the tensions used in this study and corresponding pore diameters which have the same or stronger matric potential with each tension. Under tension 13 cm, the connecting pores equal to or smaller than 0.023 cm in diameter can absorb the water from the infiltrometer. Tension 10 cm allows the connecting pores equal to or smaller than 0.03 cm in diameter to absorb the water. This does not mean that a tension of 10 cm measures only the connecting porosity between 0.02 and 0.03 cm in diameter, but pores between 0.02 and 0.03 cm can be derived by comparing infiltration rates at the tensions of 13 cm and 10 cm. The corresponded pore sizes were calculated using the following capillarity equation (Watson & Luxmoore, 1986)

$$r = -\frac{2\sigma cos\alpha}{pgh} \fallingdotseq -\frac{0.15}{h}$$

where r is the equivalent radius of tube, σ is the surface tension of water, α is the contact angle between the water and the pore wall (assumed to be 0), ρ is the density of water, g is the acceleration of gravity, and h is the water pressure of the tension infiltrometer.

Table 4.3. Four tensions given to the infiltration measurement and the corresponding pore diameters (Wilson & Luxmoore, 1988)

Tension (cm)	Matric potential (kpa)	Pore diameter (cm)
13	-1.47	≤ 0.023
10	-1.17	≤ 0.03
6	-0.77	≤ 0.05
3	-0.47	≤ 0.1

Infiltration measurements were carried out immediately after the K_{sat} measurement, so soil moisture was near a saturated level. To ensure a better contact with the membrane, the surface was flattened again with adding some mineral soils additionally when it needed. The main tube was filled with water and an initial water level was recorded. After 13 cm of water was filled in the tension tube, the infiltrometer was placed on a surface of the soil column (Figure 4.4). The water in the main tube started decreasing when the constant water head on the soil surface disappeared completely. A timer was set from the moment that the repacked soil started absorbing the water from the infiltrometer. The water level was manually recorded every minute. When the water decrease rate was the same at least three times, the infiltrations was considered to be stable, and the next tension was applied. Because the soils were almost saturated condition, the stable infiltration was achieved within 6 minutes. Then, the water level in the tension tube was adjusted by using a small syringe. The same process was repeated sequentially for all the tensions. Infiltration rates were expressed in the unit of cm min^{-1}.

Figure 4.4. Measurement of tension infiltration rates. The tension infiltrometer is seated on a surface of the repacked soil column.

4.2.8 Replication and data analysis

After the K_{sat} and infiltration measurements, the repacked soil mixture was removed from the column, dried, and repacked again with the same procedures to ensure the replications represent different distribution and alignment of rock fragments. The measurements were repeated three times. The normality of K_{sat} and infiltration rates was analysed through Kolmogorov-Smirnov test using Minitab 18, and all of them were normally distributed ($p>0.05$). Data were analysed by Fisher's one-way ANOVA (also using Minitab 18). Figure 4.5 shows the scheme of data analysis.

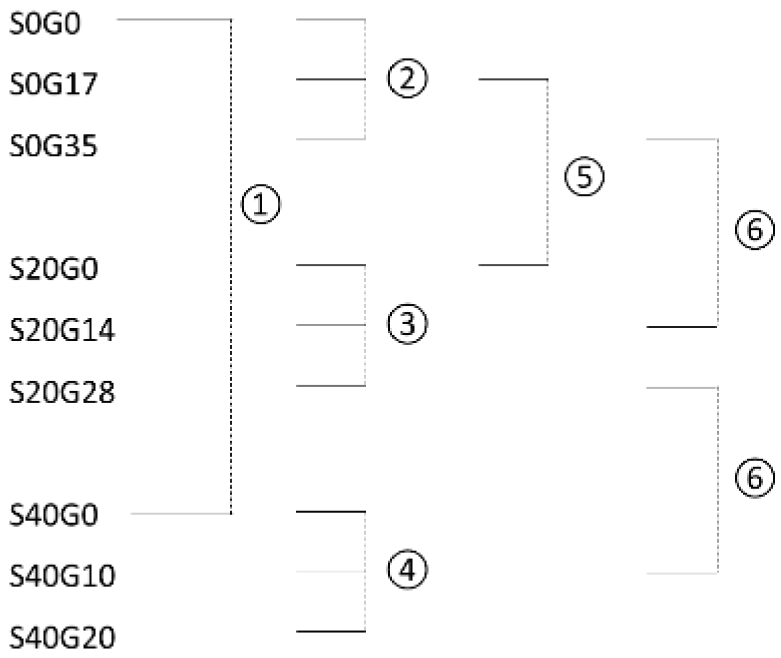


Figure 4.5. Order of data comparison for the section of Results. K_{sat} and infiltration results were compared as following groups. ① the group of 0 % gravel (S0G0, S20G0, S40G0); the groups of the same stone content ② S0G0, S0G17, S0G35, ③ S20G0, S20G14, S20G28, and ④ S40G0, S40G10, S40G20; ⑤ comparison of different sizes of rock fragments (S0G17 and S20G0); ⑥ comparison of mixed sized rock fragments (S0G35 and S20G14, S20G28 and S40G10).

4.3 Results

Table 4.4 shows descriptive statistics for K_{sat} and tension infiltration rates.

Table 4.4. Statistics for K_{sat} and tension infiltration rates. The same letters indicate no significant difference (n=3, p<0.05). The statistical test for the infiltration rates were conducted for nine values in the same column.

Treatment	K_{sat} (cm min^{-1})			Infiltration rates (cm min^{-1})											
				13 cm			10 cm			6 cm			3 cm		
	Max.[1]	Min.[2]	Ave.[3]	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.
S0G0	0.14	0.13	0.14^{b}	2.40	2.20	2.15^{ab}	3.50	2.20	3.57^{a}	5.70	4.50	5.20^{ab}	7.50	7.00	7.20^{a}
S0G17	0.18	0.16	0.17^{a}	2.80	2.30	2.55^{a}	4.85	1.60	3.18^{ab}	6.40	5.68	5.97^{a}	8.60	7.69	8.30^{a}
S0G35	0.14	0.08	0.11^{cde}	1.40	0.50	0.99^{d}	2.10	1.83	2.01^{b}	3.30	2.70	3.06^{d}	5.67	4.24	4.86^{bc}
S20G0	0.13	0.09	0.11^{cde}	2.20	1.70	1.92^{abc}	3.46	2.40	2.79^{ab}	5.20	3.80	4.45^{bc}	6.54	4.90	5.65^{b}
S20G14	0.09	0.08	0.09^{e}	1.40	0.90	1.33^{cd}	2.60	2.05	2.31^{b}	3.48	3.24	3.33^{d}	4.90	4.28	4.55^{bc}
S20G28	0.11	0.10	0.11^{cde}	2.10	0.90	1.39^{cd}	2.90	1.70	2.33^{b}	4.49	3.42	3.83^{cd}	5.62	4.05	4.76^{bc}
S40G0	0.11	0.08	0.09^{de}	1.70	1.50	1.60^{bcd}	2.43	1.60	2.12^{b}	4.00	3.01	3.52^{cd}	5.17	4.00	4.56^{bc}
S40G10	0.12	0.10	0.11^{cd}	2.20	0.80	1.55^{bcd}	3.14	1.90	2.68^{ab}	4.64	2.40	3.31^{d}	7.14	4.50	5.74^{b}
S40G20	0.12	0.11	0.12^{bc}	2.10	1.20	1.48^{bcd}	2.50	1.77	2.01^{b}	3.50	3.00	3.17^{d}	4.00	3.99	3.99^{c}

[1]Maximum
[2]Minimum
[3]Average

4.3.1 Effect of stones without gravel on soil hydraulic properties

Figure 4.6 compares K_{sat} and tension infiltration rates of S0G0, S20G0, and S40G0, which included 0, 20, and 40 % stones, respectively, with no gravel. Water flow was faster without stones. However, when the stone content increased from 20 % to 40 %, the decrease in the K_{sat} and infiltration rates were not significantly different in spite of the smaller cross-sectional area for water flow.

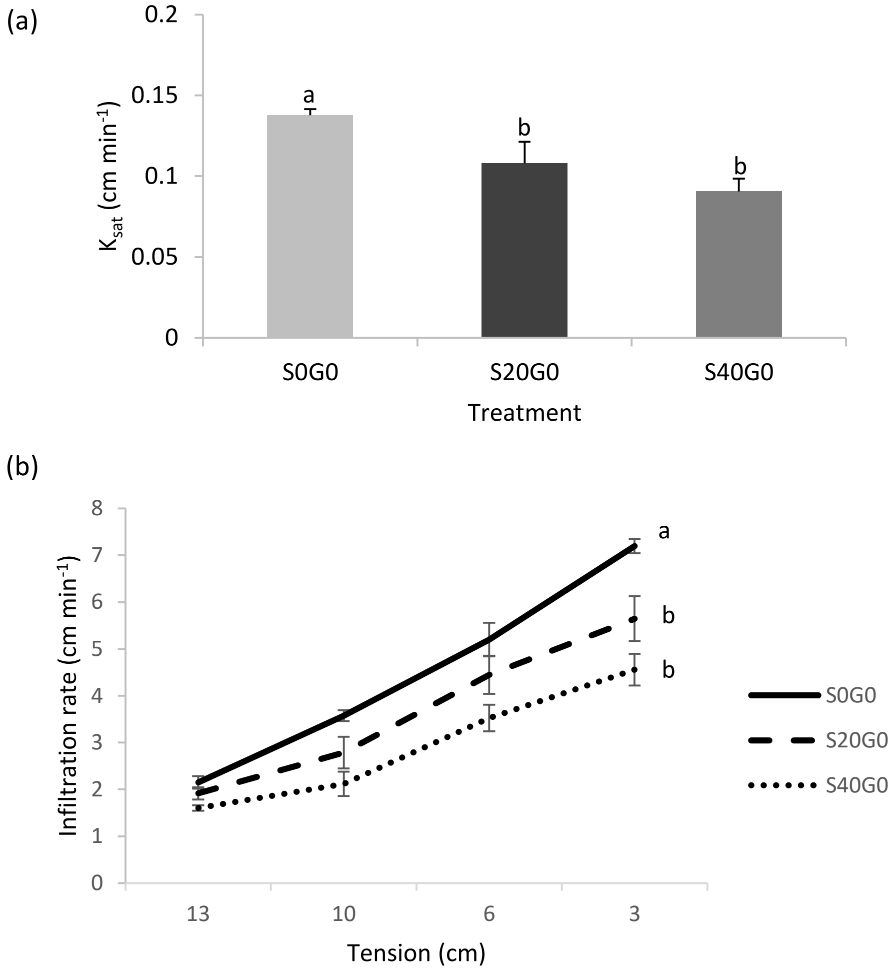


Figure 4.6. Influence of stones on (a) K_{sat} and (b) tension infiltration rates. Each treatment represents no stone (S0G0), 20% stone (S20G0), and 40% stone (S40G0). Error bars are standard errors. The same letters indicate no significant difference (n=3, $p<0.05$).

4.3.2 Effects of gravel without stones on soil hydraulic properties

Figure 4.7 shows the effect of 0, 17, and 35 % gravel without stones on K_{sat} and tension infiltration rates. While the existence of the stones decreased the values of hydraulic properties, the effects of gravel were less consistent. K_{sat} was highest at S0G17 and lowest at S0G35, which means the initial increase in the gravel content promoted water flow, but the further increase interrupted water flow. This result corresponded with the infiltration rates which was lower at S0G35. Thus, a small amount of gravel may slightly increase water flow but larger amounts substantially impede water flow. The infiltration rate of S0G17 increased rapidly from tension 10 cm to 3 cm, which implies the initial increase of gravels contributed to increasing connecting pores > 0.03 and ≤ 0.1 cm in diameter (Table 4.3). However, S0G35 decreased all the connecting pores ≤ 0.1 cm.

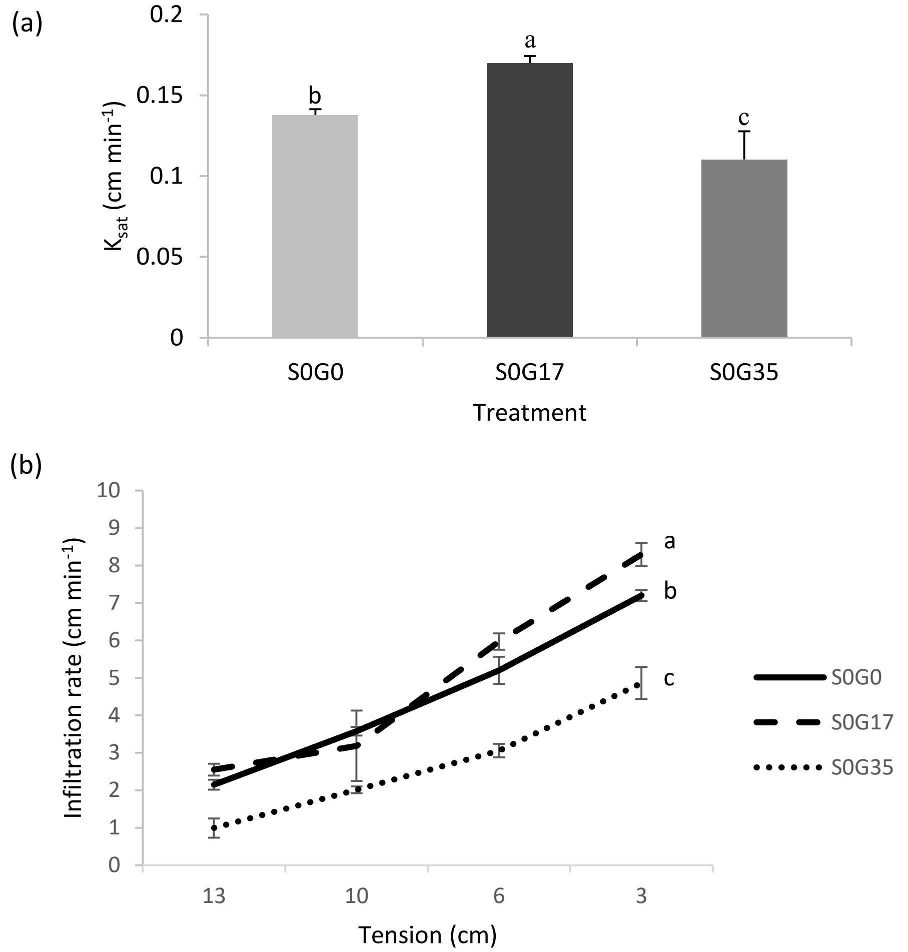


Figure 4.7. Influence of gravels on (a) K_{sat}, and (b) tension infiltration rates. Each treatment represents no gravel (S0G0), 17% gravel (S0G17), and 35% gravel (S0G35). Error bars are standard errors. The same letters indicate no significant difference (n=3, p<0.05).

4.3.3 Effect of gravel content in the presence of stones

20 % stones and increasing gravel content

In the presence of 20 % stones, gravel content had a much lesser effect on flow rates (Figure 4.8). Increasing mixed sized rock fragment content resulted in no significant difference both in the K_{sat} and infiltration rates.

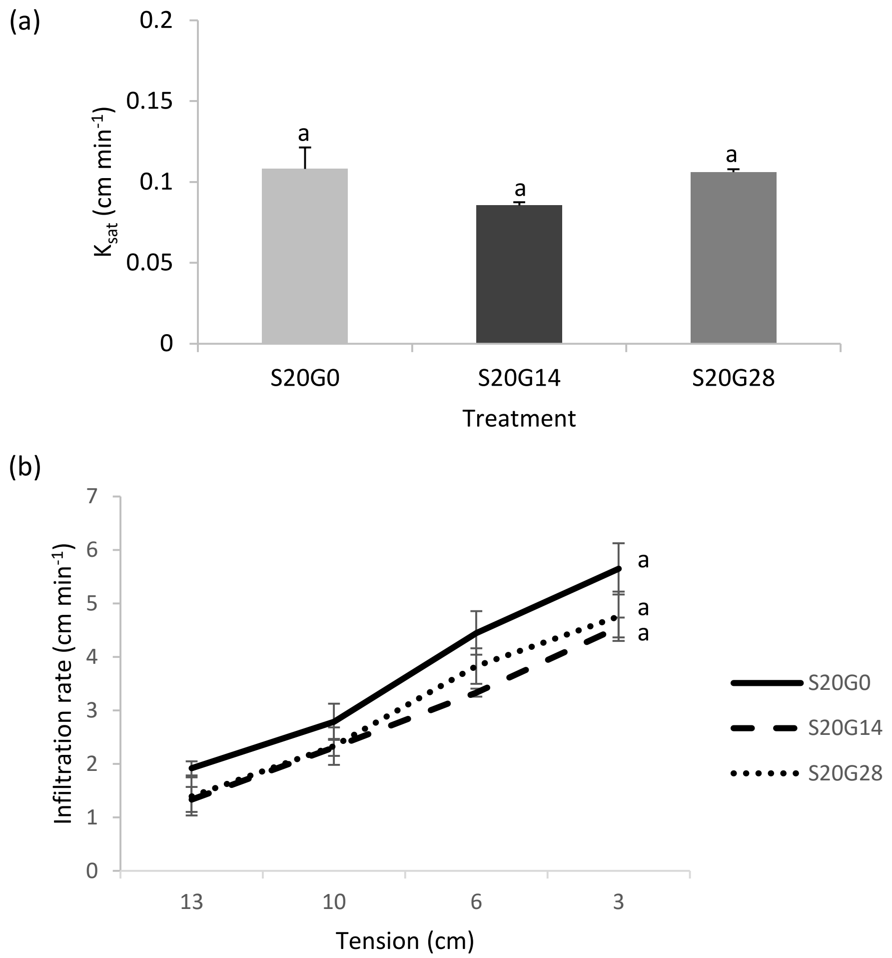


Figure 4.8. Influence of mixed sized rock fragments on (a) K_{sat}, and (b) the infiltration rates. Three treatments contain 20 % stone with no gravel (S20G0), 14 % gravel (S20G14), and 28 % gravel (S20G28), respectively. Error bars are standard errors. Same letters indicate no significant difference (n=3, $p<0.05$).

40 % stones and increasing gravels

With a higher stone content, increasing the gravel content had a similarly negligible small effect (Figure 4.9). The highest K_{sat} appeared at S40G20, and the K_{sat} values increased slightly with increasing gravel content. However, the infiltration rates at tension 3 cm were the highest at S40G10 and the lowest at S40G20.

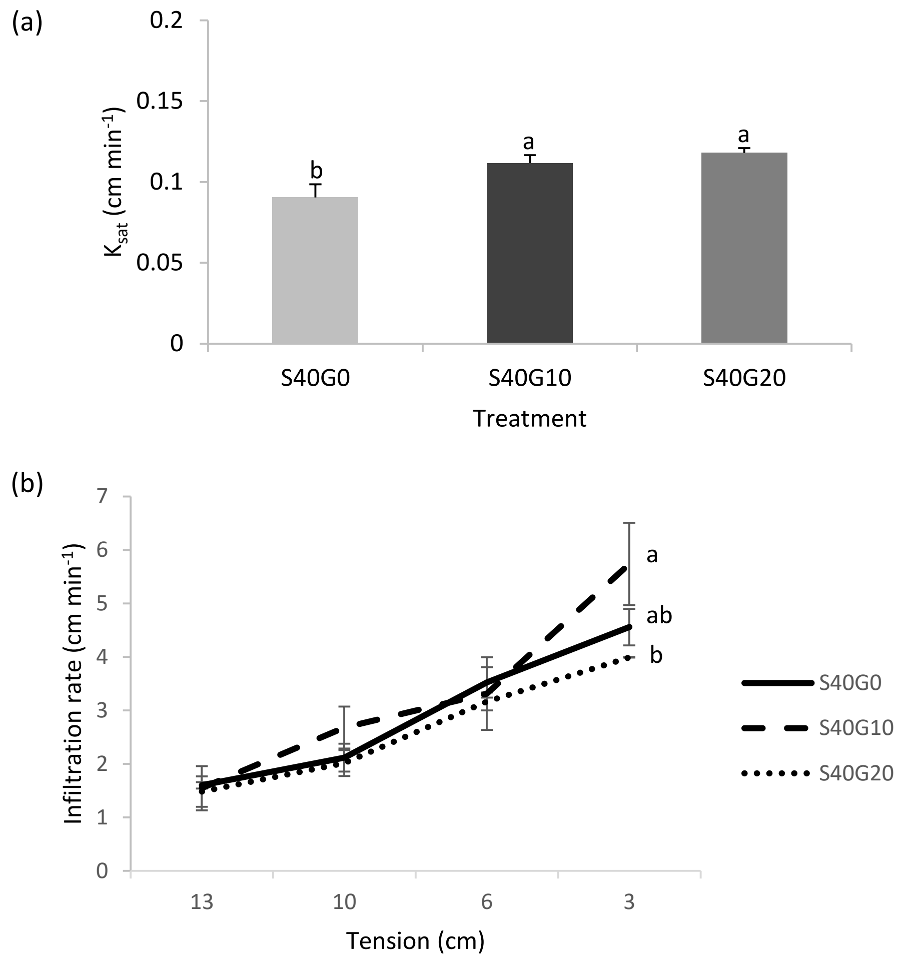


Figure 4.9. Influence of mixed sized rock fragments on (a) K_{sat}, and (b) the infiltration rates. Three treatments contain 40 % stone with no gravel (S40G0), 10 % gravel (S40G10), and 20 % gravel (S40G20). Error bars are standard errors. Same letters indicate no significant difference (n=3, $p<0.05$).

4.3.4 Comparison of variable components with smaller amount of rock fragment (c. 20 %)

Stones are more significant then gravel in slowing the rate of water flow. This is illustrated by comparing two treatments with very similar total rock fragment contents but different proportions of stones and gravel. Figure 4.10 compares the hydraulic properties of S0G17 and S20G0. Although the total rock fragment contents of S0G17 and S20G17 were similar, 17 % and 20 % each, S0G17 showed the higher K_{sat} and infiltration rates than S20G0. The higher hydraulic properties of S0G17 were unlikely to be due to the 3 % difference in total rock content because even the bigger difference of rock fragment content could not result in this huge decrease in the K_{sat} in the previous Figures. Clearly, different sizes of rock fragments were the principal causes. In conclusion, 17 % gravel was beneficial to water flow, but stones reduced water flow.

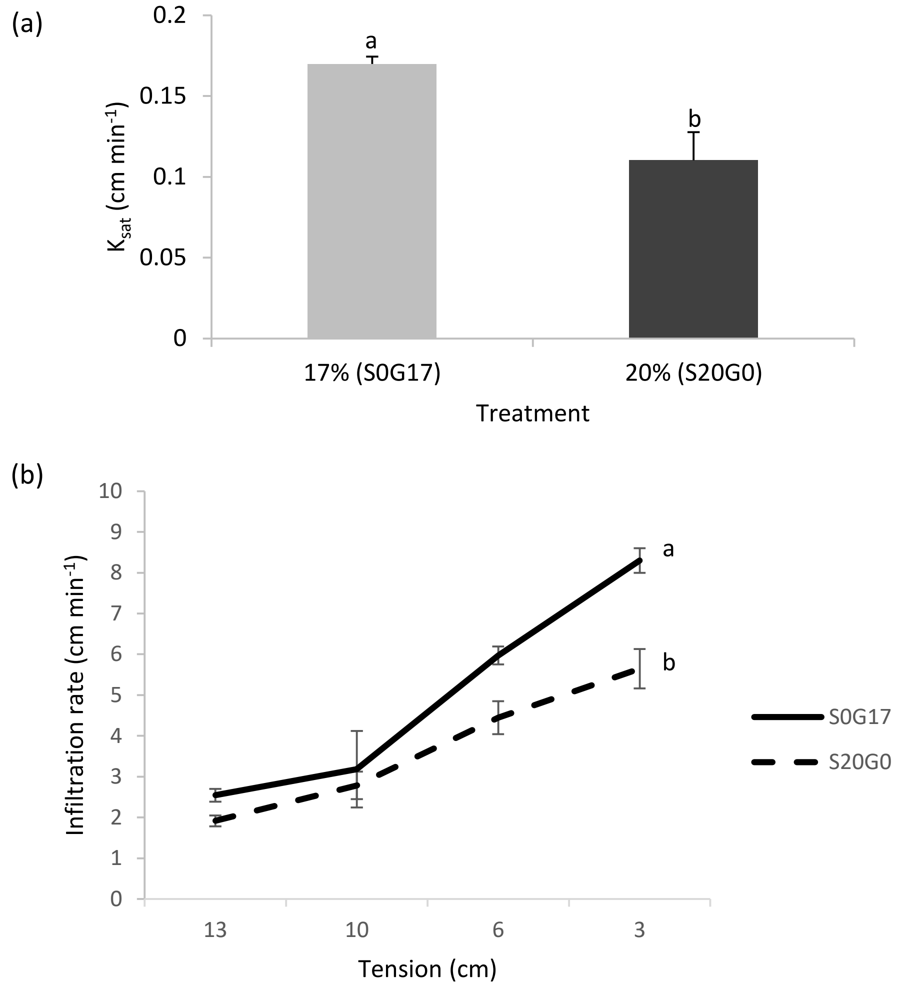


Figure 4.10. Comparison of the effects of 17 % gravel and 20% stone on (a) K_{sat} and (b) tension infiltration rates. Error bars are standard errors. The same letters indicate no significant difference (n=3, $p<0.05$).

4.3.5 Comparison of veriable components with larger amounts of rock fragment (c. 35 % and 50 %)

The component ratios of rock fragments had no significant impact on the hydraulic properties at a higher rock fragment content. Mixed size 34 % rock fragment (S20G14) and the single-sized 35 % gravels (S0G35) had similar K_{sat} and infiltration rates (Figure 4.11). Also, in Figure 4.11, both of the hydraulic properties were not significantly different at 48-50 % although the ratios of stones and gravels were completely different. Moreover, in these comparisons, the difference in total rock fragment content had no significant difference in the results.

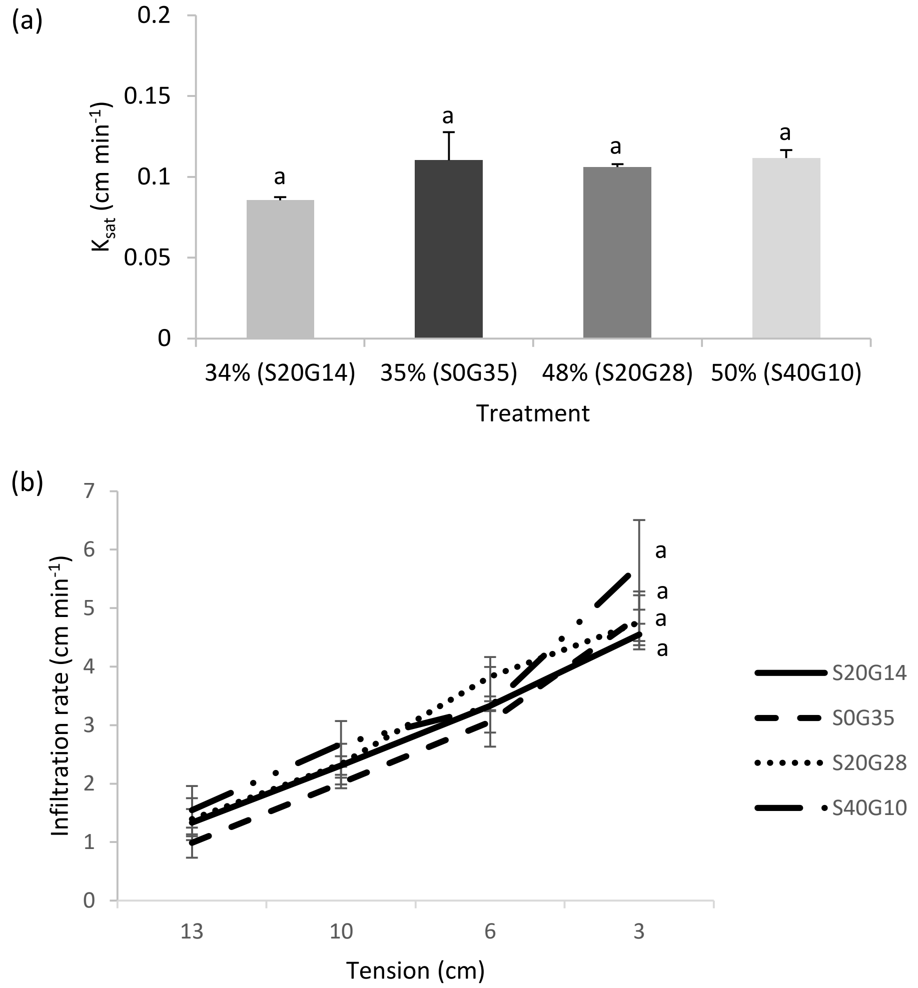


Figure 4.11. Comparison of the effect of rock fragment component ratios on (a) K_{sat} and (b) effective pores. 34% (S20G14) is consisted of 20% stone with 14% gravel, and 35% (S0G35) is only gravel with no stone. 48% (S20G28) is consisted of 20% stone with 28% gravel, and 50% (S40G10) contains 40% stone and 10% gravel. Error bars are standard errors. Same letters indicate no significant difference (n=3, p<0.05).

4.4 Discussion

4.4.1 Effects of rock fragment sizes on water flow

Influence of stone content

The K_{sat} decreased with the increasing stone content from 0 % to 20 %, but the further increase from 20 % to 40 % had no significant influence on the K_{sat} (Figure 4.6a). This result is inconsistent with the research of Novák et al. (2011) who found a gradual decrease of K_{sat} with the increasing stone content from 0 % to 50 %, regardless of soil textures. Stone occupies space in place of mineral soil, which results in less cross-sectional areas available for water flow, and a discontinuous pore systems (Beibei et al., 2009; Mehuys et al., 1975). However, when rock fragment content exceeds a critical point, the rock fragments are likely to be in contact with each other (Beibei et al., 2009). Rock fragments create large pores at rock-to-soil interfaces, and contact between rock fragments connects the large pores as a continuous flow path along surfaces of the rock fragments (Urbanek & Shakesby, 2009). In the present study, at 20 % rock fragment content, it is assumed that the stones were apart from each other, surrounded by mineral soil, and the rock content was insufficient to for much rock-to-rock connection. Although the 20 % stones may have created large pores at their surfaces, the pores were isolated and could not have a significant contribution to enhancing water flow (Lipiec et al., 2006). Furthermore, the isolated pores are more likely to interrupt water flow by trapping air (Beibei et al., 2009). The findings suggest the critical content which creates the stone contact is between 20 % and 40 % in Eyrewell soil. The difference with the study of Novák et al. (2011) might be because they used larger stones than the present study, which reduced the number of stones at the same stone content, and eventually, there would be a low possibility to create the rock-to-rock connection.

Influence of gravel content

Gravels showed both positive and negative effects on hydraulic properties (Figure 4.7). The effect of gravels on water flow has been argued elsewhere (Table 4.5). The results of the present study are most similar to Ma et al. (2010); they used sand and found an initial increase and a following decrease in K_{sat}. The gravel percentages at which the increase and the decrease appeared (8 % and 16 % respectively) were different to the present study (17 % and 35 %), but I used a wider range of gravel size (2-75 mm), and my repacked soils were more compressed (1.7 g cm^{-3}). The four studies in Table 4.4 used different size ranges, mineral soil texture, and mineral soil bulk density, which probably explain the defferences. Moreover, according to Sauer and Logsdon (2002), the origin of rock fragments (weathering, colluvial, or alluvial) and adhesion between rock fragments and the surrounding mineral soil could influence hydraulic continuity. This indicates that the effect of increasing gravel content depends on properties of soil and rock fragments. Therefore, the effect of gravels would be expanded to also differ by region.

Table 4.5. Different findings on the effect of gravels on K_{sat} in repacked soils.

Authors	Gravel size (mm)	Mineral soil texture	Mineral soil bulk density (g cm^{-3})	K_{sat} with increasing gravel content from 0 to 40 %
Beckers et al. (2016)	10-20	Clay	1.5	No significant difference
Zhang et al. (2011)	5 (beads)	Silt loam	Not mentioned	Slightly decreased from 0 to 23 %, and increased at 35 %
Ma et al. (2010)	10-20	Sand	1.5	Increased at 8 %, decreased from 16 to 25 %, and increased again at 35 %
Beibei et al. (2009)	10-30	Clay loam	1.4	Constantly decreased

Comparision of the effects of stones and gravels

The stones and gravels showed the opposite effects on K_{sat} even when they occupied a similar volume in the repacked soils (Figure 4.10). The stone decreased the values of hydraulic properties significantly, but smaller amounts of gravel increased the values of hydraulic properties. Novák et al. (2011) also reported that gravels (5 cm) induced the higher K_{sat} than the same volume of stones (10 cm and 20 cm diameter). Because gravels are smaller than the stones, the number of gravel is much higher than the number of stones at the same volume. In the present study, 20 % stones amounted to only 3-4 pieces, but the 17 % gravels might be > 100. Consequently, gravels had a larger surface area than stones, creating rock-to-soil interfaces more frequently. Thus, the soil with gravels had a higher porosity than soil with the stones. The higher number of pieces of gravel would be more likely to make contact with each other, creating a rock-to-rock flow path. Thus, the gravel and stone had different effects on K_{sat}, but this appeared only at around a 20 % rock fragment content.

4.4.2 Effects of higher rock fragment contents on water flow

The size of rock fragments had an influence on K_{sat} at around 20 % (Figure 4.10), but the K_{sat} was not affected by the size or the component ratio of rock fragment at around 35 % and 50 % (Figure 4.11). This indicates the rock fragment sizes and component ratios seem not to be important factors when total rock fragment content increases (Figures 4.8 and 4.9). This needs to be understood with a viewpoint of total rock fragment content. Figure 4.12 presents the K_{sat} values with the total rock fragment content regardless of the rock fragment sizes and component ratios. The K_{sat} values were not significantly different at the rock fragment contents between 20 % and 48 % and tended to increase gradually from 40 % to 60 %.

Intermediate rock fragment content and K_{sat}

Urbanek and Shakesby (2009) found that a range of intermediate rock fragment content induces inconstant and variable water flow rates, and this appeared in the region of 20-40 % in the present study. The rock fragments have not only a negative influence on water flow by reducing space available for water flow and increasing tortuosity, but also a positive effect by creating large pores at rock-to-soil interfaces and connecting them as rock-to-rock flow paths (Beckers et al., 2016; Beibei et al., 2009; Mehuys et al., 1975; Sauer & Logsdon, 2002; Urbanek & Shakesby, 2009). These contrary differences occur simultaneously, and the final effect depends on which is larger. The degree of the negative effect directly depends on the volume of rock fragments, as increasing rock fragments reduces the space available for water flow. However, the degree of this positive influence is affected by not only the rock fragment content but also distribution and alignment of the rock fragments. When the favorable distribution and alignment are created, the positive effect would become stronger in spite of the same rock fragment content (Urbanek & Shakesby, 2009). At the low content (17-20 %), in the present study, the size of rock fragment was likely to be a critical factor to decide whether the rock fragments contacted each other or not, as explained in the previous section. However, the intermediate rock fragment content (20-48 %) would be sufficient to generate rock-to-rock connections regardless of the size or the component ratios. In addition, increasing rock fragment content would increase rock-to-soil interfaces and rock-to-rock connections. While the positive effect gradually increased with the increasing rock fragment within the intermediate content zone, the negative effect was also gradually increased. Consequently, the contrary effects of rock fragments compensated each other, so the K_{sat} was not significantly changed.

Standard error bars at the intermediate content zone were relatively larger than the other rock fragment content (see Figure 4.12), which means the degree of the positive effect became different whenever the soils were repacked again. Similarly, Sakaki and Smits (2015) found that porosity of repacked soils varied at each time of repacking. This is because a packing procedure or uniformity of repacked soil enable to affect K_{sat} (Beckers et al., 2016; Zhang et al., 2011) because the distribution and alignment of rock fragments would be altered every time. The result of the present study suggests the K_{sat} at the intermediate rock fragment content is variable in a repacked soil experiment, which makes interpretation of the result more complex.

High rock fragment content and K_{sat}

Increase in the K_{sat} at high rock fragment content is consistent with the previous studies. In particular, many studies have reported that the K_{sat} rapidly increased when the rock fragment content was over than 40 % (Beckers et al., 2016; Beibei et al., 2009; Zhang et al., 2011). This would be because a high volume of rock fragment creates large gaps between the rock fragments. According to Sakaki and Smits (2015), less-filled or unfilled voids were commonly generated in a mixture of two sized particles, especially when the ratio of coarser particles was high. Van Wesemael et al. (1995) also reported a strong increase in macropores when the rock fragment content was greater than 50 %. The repacking process was not properly conducted in the present study because of the huge volume of rock fragments, so the unfilled voids were obviously recognized. Moreover, the present study demonstrated the high K_{sat} at S40G20 (60 %) although the tension infiltration rates were very low (Table 4.4), which implies a lot of large pores were created in S40G20. Water flows through all of connecting pores regardless of sizes when soil is saturated, but the tension infiltration test in the present study estimated a limited range of connecting pores up to 0.1 cm diameter (Figure 4.13). Therefore, the inconsistent hydraulic properties of S40G20 implies the pores larger than 0.1 cm were created in S40G20. Due to this void, water could flow fast although the rock fragments accounted for large space in the soil. Because this fast flow was caused by the repacking, this may or may not happen under natural conditions.

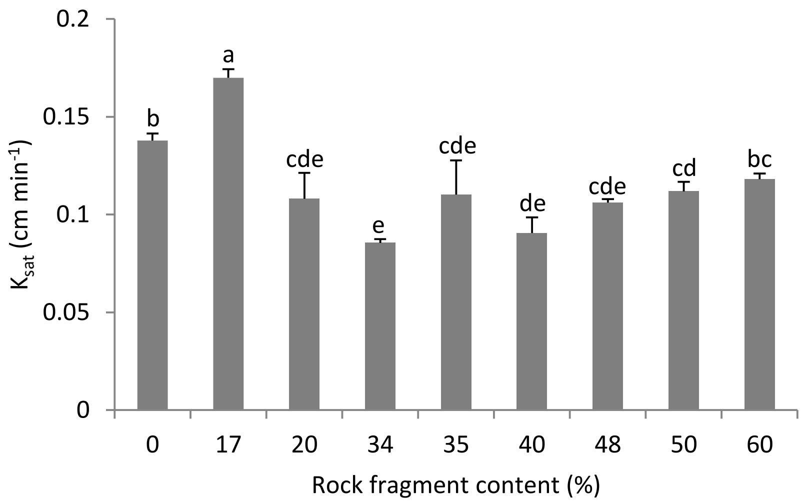


Figure 4.12. K_{sat} with total rock fragment content. Error bars are standard errors (n=3). The same letters indicate no significant difference (n=3, $p<0.05$).

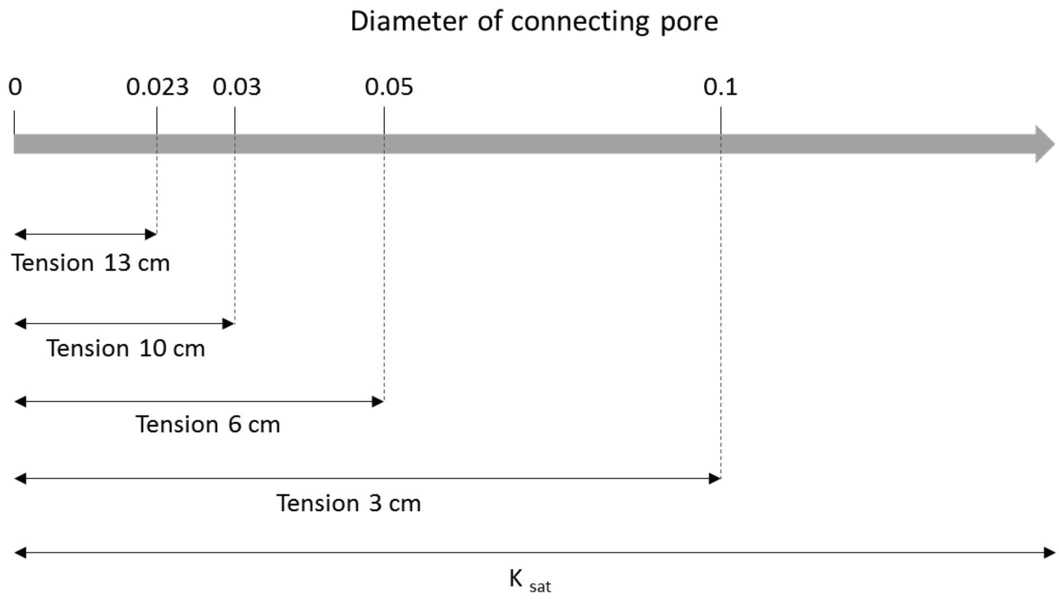


Figure 4.13. Ranges of diameter of connecting pores related to K_{sat} and infiltration rates with different tensions.

Relationships between rock fragment content and connecting porosity

Figure 4.14 shows the negative relationship between the rock fragments and the tension infiltration rates at all tensions. The relationship was strongest at tension 10 cm (R^2=0.67), and R^2 values gradually decreased with decreasing tensions, which means the pores larger than 0.03 cm were likely to reduce the correlation (Figure 4.13). Therefore, sizes of rock-to-soil interfaces and continuous flow paths along the rock fragments, which increased with increasing rock fragment content, seem to be larger than 0.03 cm.

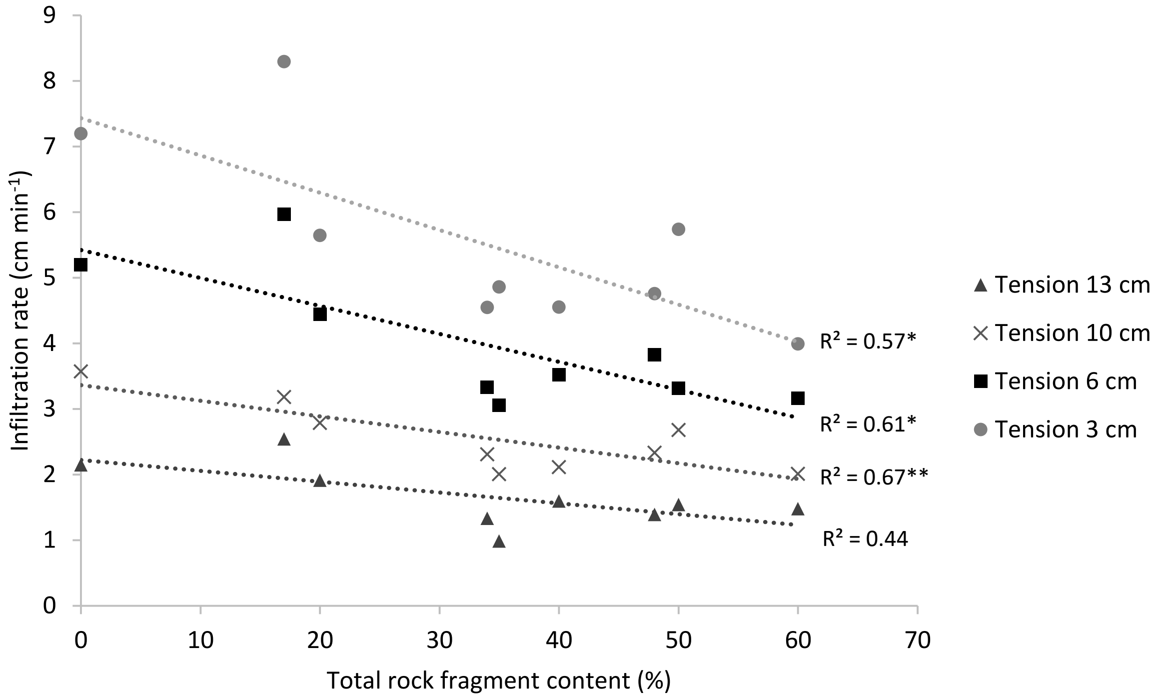


Figure 4.14. Relationships between rock fragment content and tension infiltration rates with four tensions (*: $p < 0.05$, **: $p < 0.01$).

4.5 Conclusions

Hydraulic properties, measured as K_{sat} and tension infiltration rates, substantially differed in repacked soils containing increasing single-sized and mixed-sized rock fragment contents. The rock fragments had different effects on water flow depending on total rock fragment content, leading the following conclusions:

Ⅰ. Stones reduce water flow, but gravel enhances water flow at a low rock fragment content (17-20 %). The size of rock fragments was a critical factor for the K_{sat} at low rock fragment content because the existence of rock-to-rock connections was closely related to the size of rock fragments. Where 3-4 pieces of stones were isolated, a large number of pieces of gravel was more likely to create rock-to-soil interfaces and continuous flow paths along surfaces of rock fragments.

Ⅱ. An intermediate content of rock fragments had no significant effect on hydraulic properties. At intermediate rock contents (20-48 %), the K_{sat} was not influenced by the increasing content, size, and component ratios of rock fragments. This was because the content was sufficient to create the rock-to-rock connections regardless of the size and the component ratios. Increasing rock fragment content not only decreased space available for water flow but also increased the large pores at rock-to-soil interfaces and the rock-to-rock connections. Distribution and alignment of rock fragments had the relatively larger effect on the K_{sat}, which resulted in large standard error bars.

Ⅲ. At a high rock fragment content (40-60%), the K_{sat} tended to increase gradually. When the rock fragments accounted for large space in the repacked soil, less-filled or unfilled voids were created between rock fragments. This may be a limitation of the repacking experiment and may or may not happen to the same degree in the field. When the rock fragment content increased, the soil could not be repacked properly, which is a limitation of laboratory scale experiment. Further study is necessary to explore the effect of rock fragments on water flow in field conditions.

Ⅳ. This part of the study has provided valuable knowledge of the significance of rock fragments to hydraulic properties of Eyrewell soil. An optimal range of rock fragment of 20-48 % regardless of sizes or component ratios, would restrict the leaching of water through the soils. Lack of rock fragments would enhance leaching depending on distribution and alignment of rock fragments. It is recommended that rock fragments should not be removed from engineered agricultural landscapes, as was the case during the forest-to-farm conversion.

Chapter 5
Effects of rock fragments and plant roots on soil water flow and nutrient leaching

5.1 Introduction

Leaching of soil nutrients decreases the efficiency of agricultural input and causes serious groundwater contamination (Schoen et al., 1999). The most common pollutant found in groundwater is nitrate (NO_3^-) (Postma et al., 1991), with fertilizers and manures providing the major sources (Almasri & Kaluarachchi, 2004). When nitrogen input exceeds plant requirements and the capacity of soil denitrification, nitrogen permeates into groundwater as the form of nitrate (Almasri & Kaluarachchi, 2004). Critical nitrate concentration in groundwater causes eutrophication and human health problems (Nolan & Stoner, 2000). Therefore, studies on nutrient leaching from soils are potentially highly valuable.

Solute movement is closely related to soil hydrological processes. Factors that are to soil water flow, such as rock fragments, are also strongly connected with solute transport. Plant root channels are one type of macropores which have a large impact on soil water flow by acting as preferential flow paths (Ghestem et al., 2011). Furthermore, these factors are related because rock fragments are known to have an impact on plant biomass, height, stems, and roots (Mi et al., 2016; Qin et al., 2015); rock fragments and plant roots would be expected to have a combined effect on hydrological processes in soils. Little attention has been given to the effect of these factors on nutrient leaching in Eyrewell soils that are highly stony and mostly covered by plants.

Tracers have been commonly used to understand solute transport in soils containing rock fragments. Tracer elements are not important for plant growth and, of course, usually do not exist in soils. Bromide is one of the most suitable conservative tracers for nutrient leaching studies (Kung et al., 2000) due to its low biological reactivity (Schnabel et al., 1995). Whereas nitrate can be transformed into nitrous oxides and molecular nitrogen by denitrification, bromide is more stable and mostly lost by leaching. Thus, bromide is likely to simulate the worst case scenario of nitrate leaching in soils (Tilahun et al., 2006).

Research reported in this chapter aimed to investigate the influence of rock fragments and plant roots on nutrient leaching in Eyrewell soil using a pot-scale experiment. Two different plant species (maize and ryegrass) were used to investigate the effect of root systems on leaching. Nitrate leaching was investigated first, and bromide was then used as a tracer to track solute transport and to estimate solute recovery from lechate and soils.

5.2 Materials and methods

5.2.1 Soil preparation

Soil samples were collected as described in Chapter 4.2.1. The collected soils were moved to a laboratory and sieved (see Chapter 3.2.4). Properties of mineral soils are described in Chapter 4.2.5.

5.2.2 Establishment of pot experiment

Black plastic planter bags, 37 cm in length and 15 cm in diameter, were filled with mineral soils and gravel to provide 0 % and 25 % stoniness by volume. The 25 % stoniness was a representative of the intermediate rock fragment content which was found to be optimal to restrict water flow in Chapter 4. Stones were too large for the planter bags, so only gravels were used in the present experiment. One treatment (0 % gravel soils) had 8.5 kg of mineral soils filling the planter bags. A second treatment (25 % gravel soils) contained 5.5 kg of mineral soil and 3.3 kg gravel. Mineral soil bulk density of 0 % gravel soils was 1.7 g cm^3, and that of 25 % gravel soils was 1.5 g cm^3. They were mixed in a large container and packed in the planter bags uniformly. Depth of the repacked soils was 29 cm, with a total volume of 5.1 L. Maize and ryegrass were selected for this study because they have different root systems; maize has a thicker and deeper root, and the root system of ryegrass is thinner and denser. Seeds of each plant were germinated in a separate pot, and then two rooted tillers of maize (M) and 60-70 rooted tillers of ryegrass (R) were transplanted into each repacked soil. A third reference treatment contained no plants. Treatments are illustrated in Figure 5.1. Abbreviations of each treatment include plant treatments (M, R, and C), and rock fragment treatments (0 and 25). The six treatments each had three replicates, so a total of eighteen pots were maintained in a greenhouse (Figure 5.1). They were irrigated with 200-500 ml (11.3 - 28.3 mm in depth) of water every day, depending on a day temperature for five months from November to April (2017-2018). A commercial liquid fertilizer (High NK, PGG Wrightson Turf) was applied (15 L ha^{-1}) twice in January with a two week interval. Leaching experiments were carried out in February with nitrate and April with bromide.

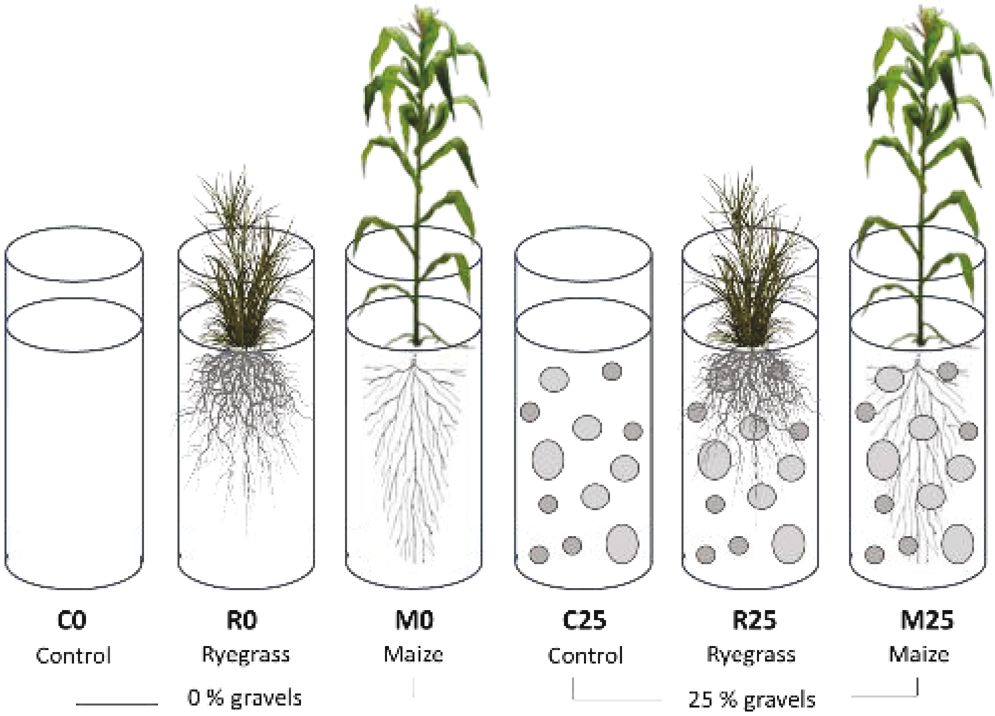


Figure 5.1. Treatments of pot experiment and their abbreviations. There are two groups of rock fragment treatments (0 % and 25 %) and three groups of plant treatments (maize, ryegrass, and control).

5.2.3 Solute transport experiment

Effects of rock fragments and plant roots on nutrient leaching were investigated by applying nitrate and bromide solution and measuring the Electronic Conductivity (EC) of the leachate. Before applying the solutions, soils were almost saturated because of the long-term of intensive irrigation.

Nitrate transports

Volumes of 500 ml of KNO_3 solution (1.5 g L^{-1}, 2030 µS cm^{-1}) were applied to each soil, and leachate was collected (Figure 5.2). After drainage stopped, a volume and EC of the leachate were measured using a volumetric cylinder and an EC meter (HQ20D portable multi meter, HACH). A volume of 500 ml of water was applied twice a day in the morning (8-9am) and afternoon (3-4pm), and the leachate was collected and measured each time. The water application and leachate collection were conducted eight times until EC of the leachate returned to a beginning level. Then, experiment was repeated three times. During the second experiment, the leachates after the first, fourth, and fifth water application were sampled, and nitrate concentrations were analysed using FIA star 5000 triple channel analyser (Foss Tecator AB, Sweden). A regression equation between EC and nitrate concentration of the leachate was obtained (Figure 5.3). By using this equation, EC values, and leachate volumes, amounts of nitrate (mg) in the leachate was calculated. Data were analysed by Fisher's one-way ANOVA using Minitab 18.

Figure 5.2. Pot experiment. Leachate collected in white plastic boxes under each pot.

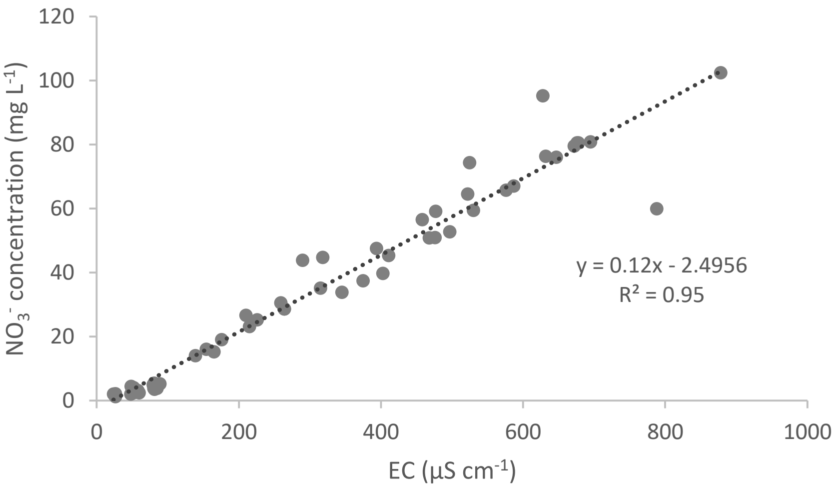


Figure 5.3. Relationship between measured EC (µS cm^{-1}) and nitrate concentration (mg L^{-1}) of leachate, and regression equation.

Bromide transports

Volumes of 500 ml of KBr solution (1.8 g L^{-1}, 2016 µS cm^{-1}) were applied to each soil in a bromide transport experiment that was carried out only once. An overall procedure was the same as the nitrate transport experiment, but water application and leachate collection were repeated nine times. This was carried out on the same pot experiment described above. A relationship between EC and bromide concentration was obtained by step dilution of KBr solution. KBr solution (5.4 g L^{-1}) was diluted using a serial dilution, and bromide concentration of each diluted solution was calculated. EC of each solution was measured, and a regression equation between EC and bromide concentration was obtained (Figure 5.4). This equation assumed that a change of EC was caused only by bromide. However, leachate actually included a lot of other elements which could affect EC. Thus, EC of the first leachate, which had no bromide, was considered as a background value, and EC increase of each leachate was assumed to be caused only by bromide. Increased EC of leachate, which was subtracted the background EC from measured EC, was substituted to the equation, and bromide concentrations of leachates were calculated. The total amount of bromide (mg) was calculated by multiplying leachate volumes and the bromide concentration of leachate. Data were analysed using Fisher's one-way ANOVA using Minitab 18.

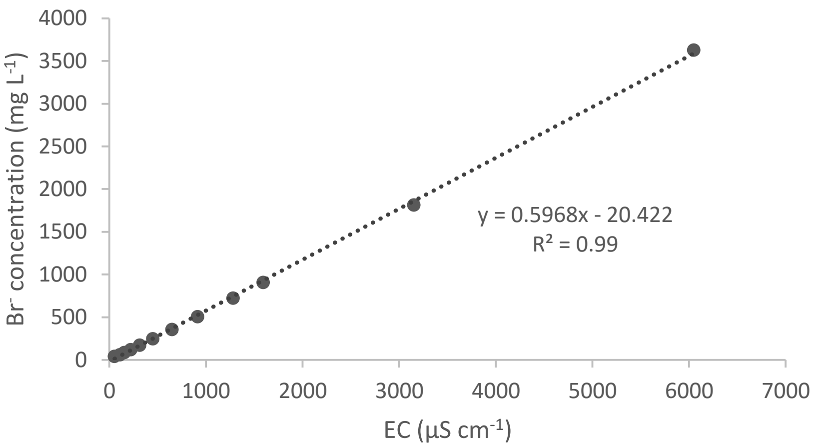


Figure 5.4. Relationship between measured EC (µS cm^{-1}) and calculated bromide concentration (mg L^{-1}) in solutions, and regression equation.

5.2.4 Plant sampling and measurement

After the bromide transport experiment, plant shoots were harvested and placed in paper bags. Each planter bag was cut, and the side surface of each soil and roots was photographed. The soils were divided into 0-15 cm and 15-30 cm from the top. The roots exposed on the outside of the soil were carefully detached, and the roots inside the soil were collected after breaking a shape of the soil. The sampled roots were washed using tap water to remove soil particles and placed in paper bags. Plant samples were dried in the oven at 65℃ for three days, and dry mass was weighed. Data were analysed by Fisher's one-way ANOVA using Minitab 18.

5.2.5 Soil sampling and bromide analysis

Depths of 0-15 cm and 15-30 cm of soil in each planter bag were separated. Each was then mixed, sampled, and air-dried for three days. Soils from the treatments with 25 % gravel were sieved to remove rock fragments, and mineral soils were used for the analysis. To measure bromide in the soil, 5 g of each soil sample was weighed and put into 50 ml plastic tubes. After 40 ml of deionised water was added, the tubes were shaken for 30 minutes using an end-over-end shaker and centrifuged at 3,000 rpm for 10 minutes. Clear solutions in the tubes were filtered through Whatman 41 papers, and then, bromide concentration of each solution was analysed by Suppressed Ion Exchange chromatography (Dionex DX-2100, USA). Bromide concentration of soil (mg kg^{-1}) was calculated using the following equation:

$$\text{Bromide concentration in soil} = Bromide\ concentration\ in\ solution \times \frac{\text{added water}}{oven - dried\ soil}$$

The added was 0.04 L, and the oven-dried soil was 0.005 kg. Then, the total amount of bromide in the soil (mg) was calculated using the mass of mineral soil and bromide concentration in soils. Data were analysed by Fisher’s one-way ANOVA using Minitab 18.

5.3 Results

5.3.1 Biomass of plants

Figure 5.5 compares dry matters of maize and ryegrass in 0 % and 25 % gravel soils. Aboveground biomasses of two plant species were similar. Shoots of maize in 25 % gravel soils significantly decreased compared to 0 % gravel soils, but that of ryegrass was not affected by gravels. Differently, underground biomass was much higher in ryegrass than maize. For both of the species, root biomass tended to decrease with the existence of gravels, but there was no statistical difference. As shown in Figure 5.6, the roots of ryegrass were thinner but root density of ryegrass was much higher than maize. Also, both species showed higher root density near top soils than deeper soils.

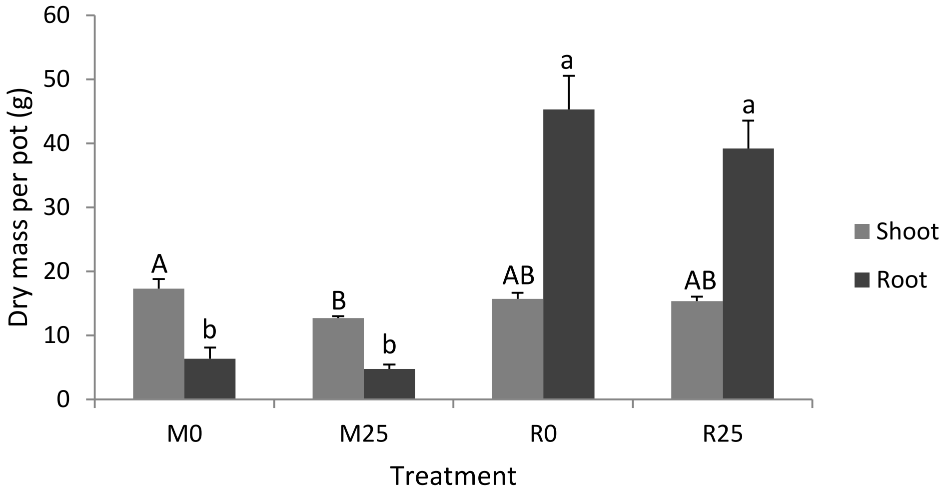


Figure 5.5. Dry matter of maize (M) and ryegrass (R) in 0 % and 25 % gravel soils. Statistical analysis of shoot and root were separately conducted. Error bars are standard errors. The same letters indicate no significant difference (n=3, p<0.05).

Maize root

Ryegrass root

Figure 5.6. Roots of maize and ryegrass grown in 0 % and 25 % gravel soils. Upper photographs show vertical view with pots. Lower photographs show view from

5.3.2 Nitrate transport experiment

Figure 5.7 shows the amounts of nitrate in leachate at each leachate collection. Without gravel (M0, R0, and C0), peaks of leached nitrate appeared in the fifth leachate regardless of plant treatment. With 25 % gravel soils, peaks of nitrate appeared in the fourth leachate. There was no difference in the volumes of each time of leachate between 0 % and 25 % gravel soils (Figure 5.8). Leachate from 25 % soils contained more nitrate and increased more rapidly in every plant treatment. This indicates nitrate leaching was faster and more intensive with the presence of gravels. Despite different leaching rates between 0 % and 25 % gravel soils, the total amounts of leached nitrate throughout the entire leachate collection was not significantly different within plant treatments but was different between plant species and with the reference pots (Figure 5.9). However, total leached nitrates throughout three replications of nitrate leaching experiment tended to be higher in the presence of gravel under the same plant treatment (Table 5.1). This suggests gravel may eventually increase nitrate leaching in the longer term.

On the other hand, maize and ryegrass had no effect on delaying nitrate peaks (Figure 5.7) However, the sums of leached nitrate under maize and ryegrass were significantly lower than control (Figure 5.9). This implies the presence of plants has a positive impact on reducing nitrate leaching, and ryegrass is more effective than maize.

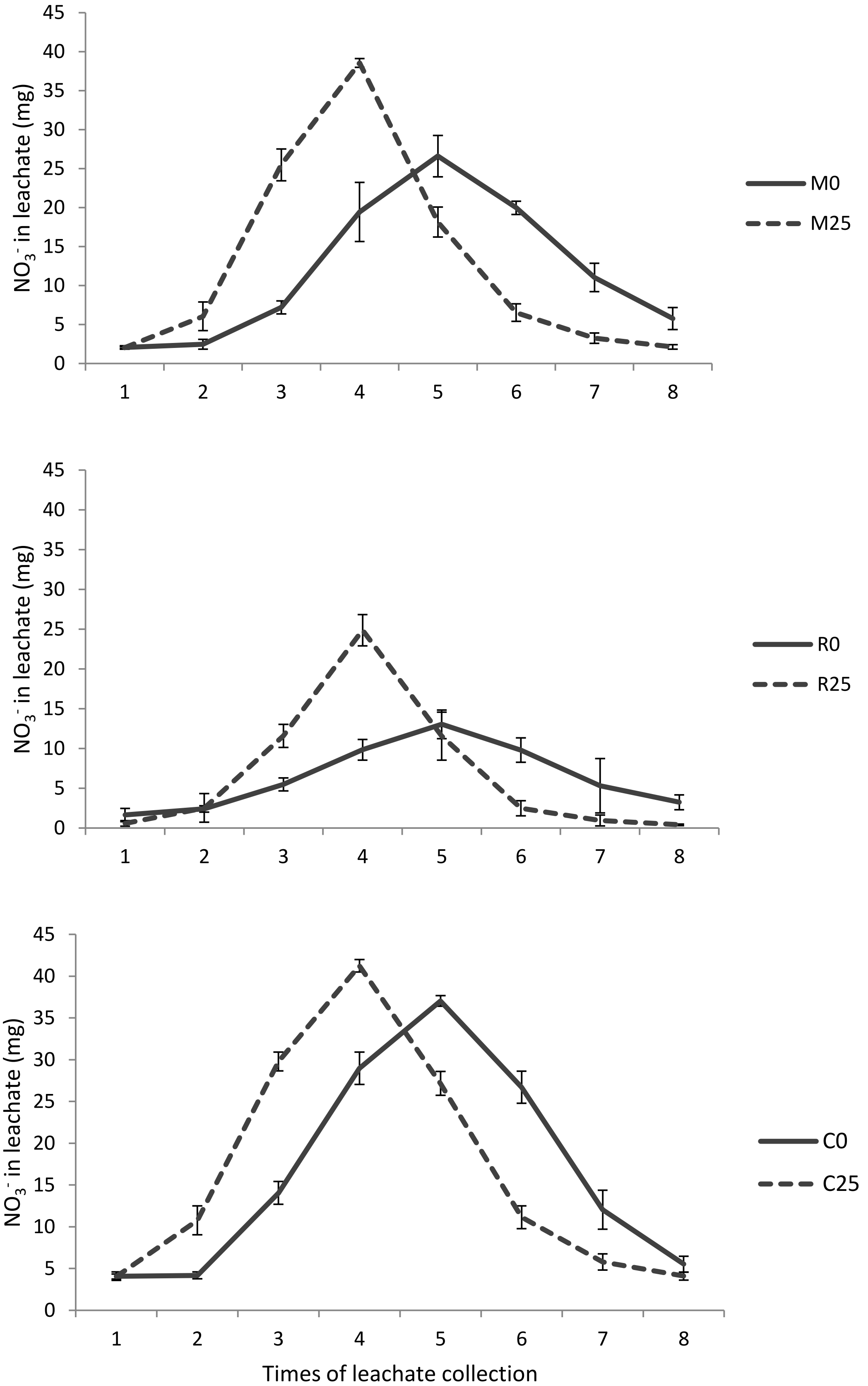


Figure 5.7. The amounts of nitrate in each time of leachate in 0 % and 25 % gravel soils with maize (M), ryegrass (R), and without plants (C). Volumes are the mean of nine measurements (three times of experiment on each pot out of three). Error bars are standard errors.

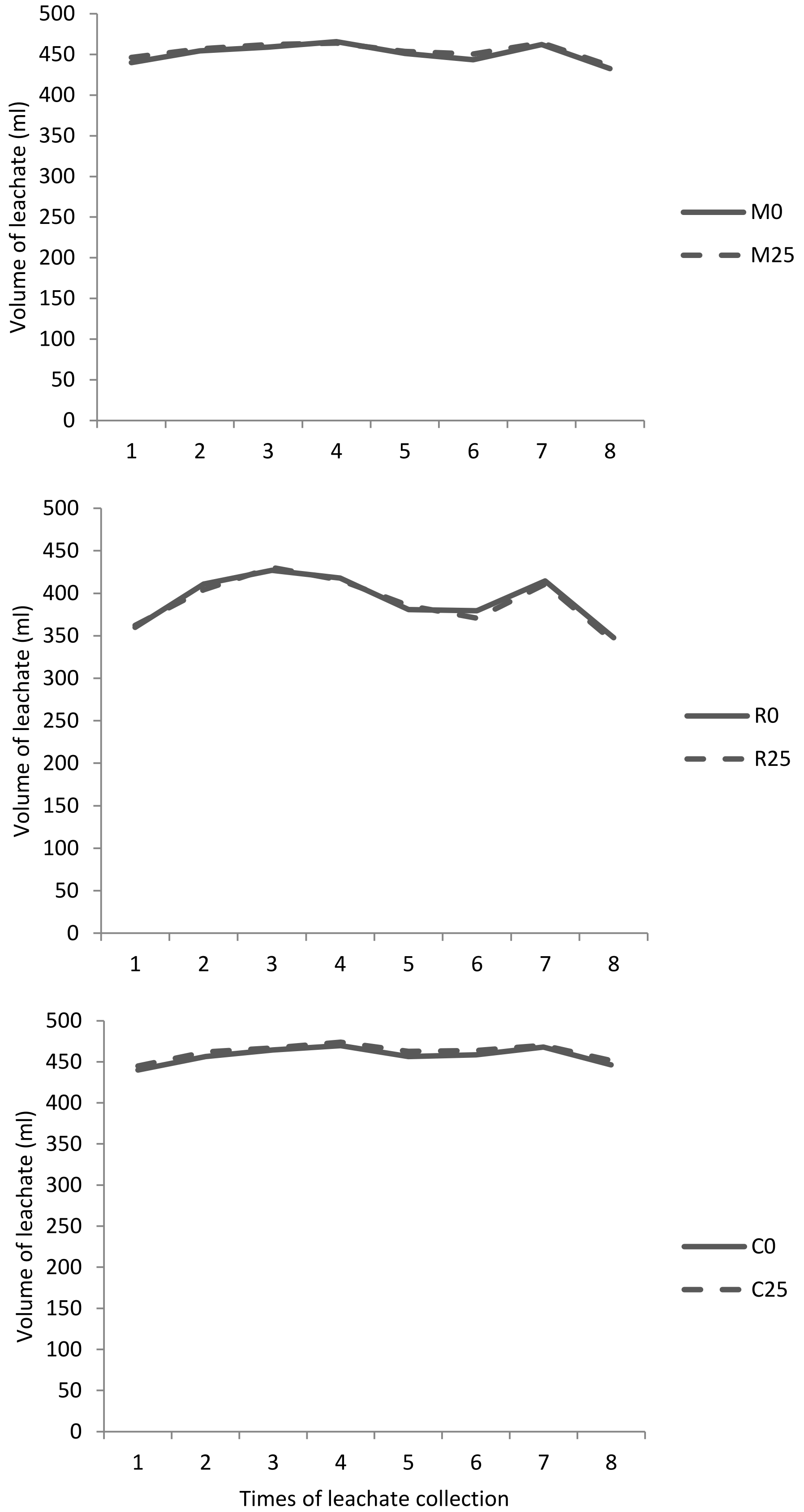


Figure 5.8. The amounts of leachate in each time of leachate in 0 % and 25 % gravel soils with maize (M), ryegrass (R), and without plants (C) during the nitrate leaching experiment. Volumes are the mean of nine measurements (three times of experiment on each pot out of three).

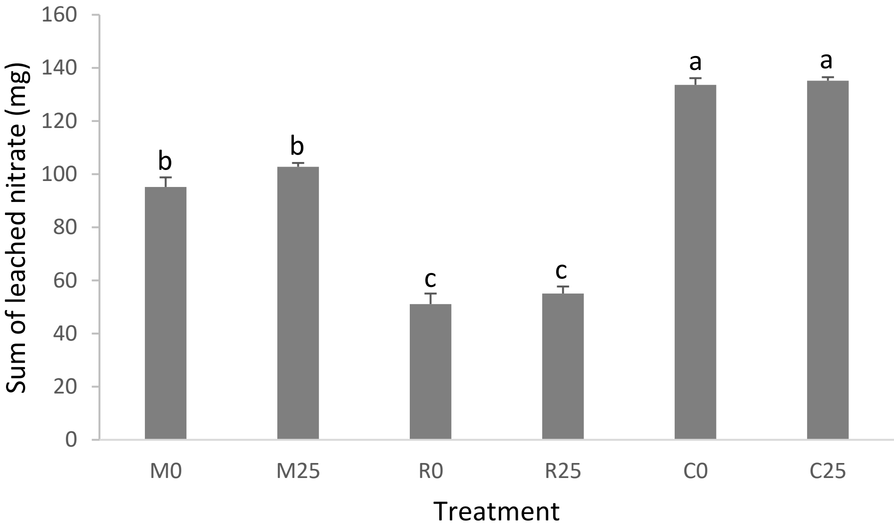


Figure 5.9. Sum of leached nitrate throughout the entire leachate collection. Error bars are standard errors. The same letters indicate no significant difference (n=9, p<0.05).

Table 5.1. Total amounts of leached nitrate from each treatment throughout three times repeated experiment.

Treatment	Sum of leached nitrate (mg)			Total (mg)
	First	Second	Third	
M0	95.6	83.3	106.6	285.5
M25	103.2	99.8	105.4	308.4
R0	62.2	43.9	47.1	153.3
R25	65.6	50.0	49.5	165.1
C0	138.6	128.2	134.2	401.0
C25	136.5	132.8	136.3	405.6

5.3.3 Bromide transport experiment

Bromide leaching through leachate

Figure 5.10 shows the amounts of bromide in leachates. Peaks of bromide appeared, like nitrate, in the fifth leachate (in 0 % gravel soils) and in the fourth leachate (in 25 % gravel soils), and the volumes of leachate each time were similar regardless of gravel (Figure 5.11). The total amounts of bromide under maize were not significantly different from the control (Figure 5.12). However, maize may also reduce bromide leaching in the longer term because total amounts of leached bromide were less in maize treatments than control (Table 5.2). Ryegrass had a significant effect on reducing bromide leaching, but the bromide reduction was smaller than the nitrate reduction.

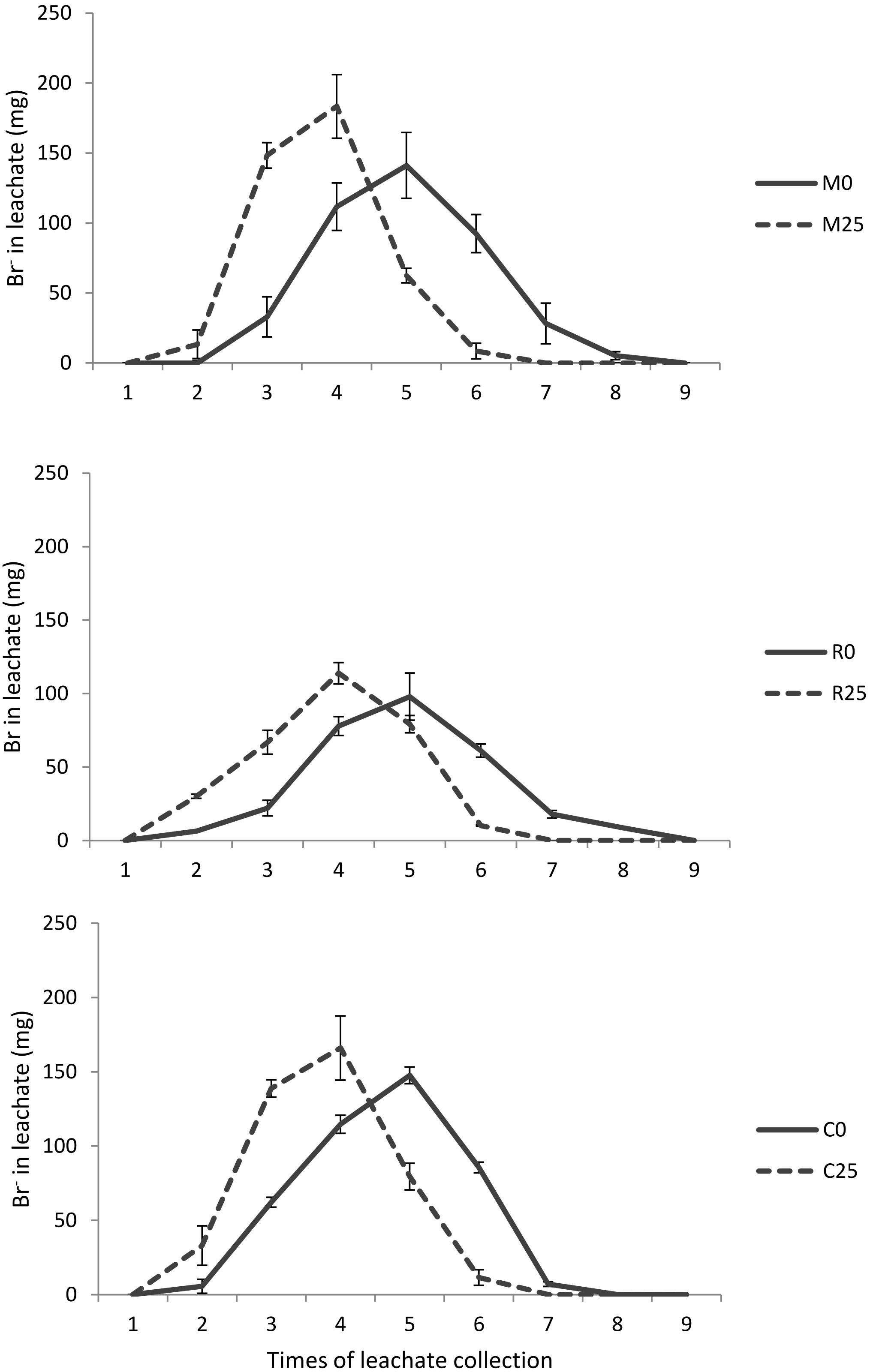


Figure 5.10. The amounts of bromide in each time of leachate in 0 % and 25 % gravel soils with maize (M), ryegrass (R), and no plant (C). This is an average of nine experimental values (three pots and three times of experiment). Error bars are standard errors.

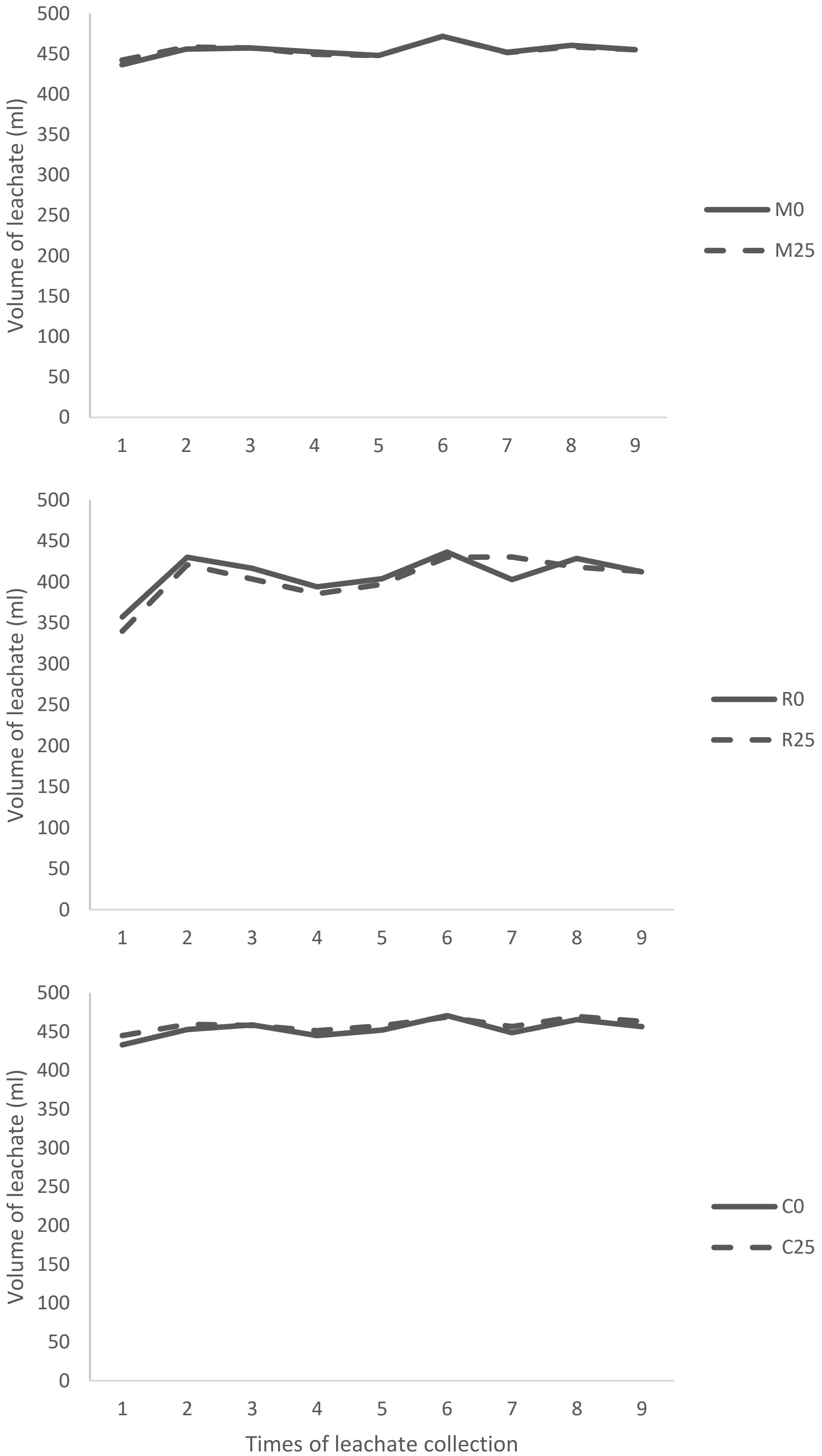


Figure 5.11. The amounts of leachate in each time of leachate in 0 % and 25 % gravel soils with maize (M), ryegrass (R), and without plants (C) during the bromide leaching experiment. Volumes are the mean of three measurements.

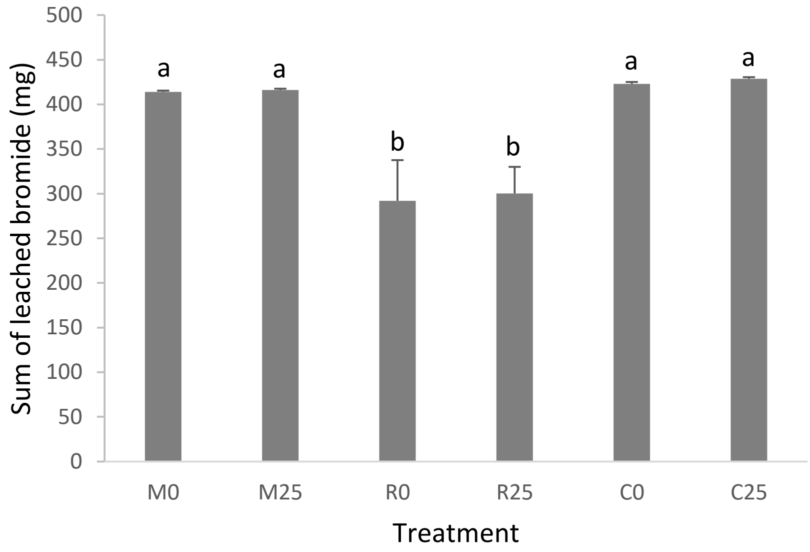


Figure 5.12. Sum of leached bromide throughout whole leachate collection. Error bars are standard errors. The same letters indicate no significant difference (n=3, $p<0.05$).

Table 5.2. Total amounts of leached bromide from each treatment during bromide leaching experiment.

Treatment	Sum of leached bromide[1] (mg)			Total (mg)
	Rep.[2]1	Rep.2	Rep.3	
M0	415.7	408.0	417.9	1241.7
M25	419.1	414.6	414.9	1248.6
R0	202.5	349.3	324.4	876.2
R25	352.6	249.0	298.8	900.4
C0	421.5	427.0	420.1	1268.5
C25	426.0	428.3	432.0	1286.3

[1]Sum of bromide through whole leachate collected eight times

[2]Replication of three pots

Bromide retained in soils

Figure 5.13 shows the concentration of bromide in mineral soils after bromide transport experiment. Nitrate concentration in the soils was not examined in the present study (see 5.4.1). Without plants (C), the bromide concentrations of mineral soils were similar regardless of gravel content and depths of the soils. However, maize and ryegrass significantly increased the bromide concentration of 0-15 cm soils, which indicates plant roots positively affect retaining soil elements. The bromide concentration was significantly or tended to be higher in 25 % gravel soils than 0 % gravel soils under the same plant treatments. However, the total bromide retained per each pot shows 25 % gravels soils tended to retain the lower amount of total bromide than 0 % gravel soils under the same plant treatments (Figure 5.14). This is because 25 % gravel soils contained fewer mineral soils, so they had the lower capacity. This indicates although rock fragments increased the bromide concentration of mineral soils, this cannot cover the reduced nutrient capacity of the entire soil.

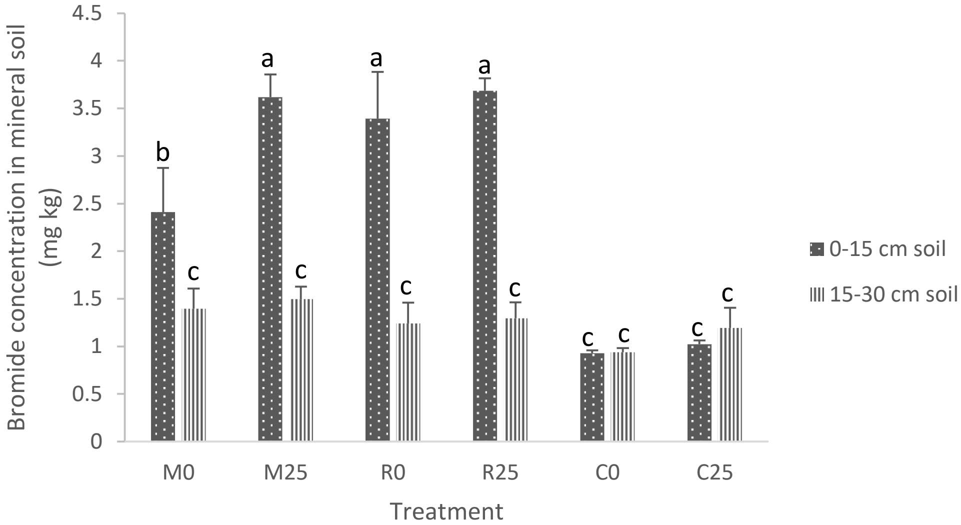


Figure 5.13. Bromide concentration of mineral soils in each treatment. Error bars are standard errors. The same letters indicate no significant difference (n=3, p<0.05).

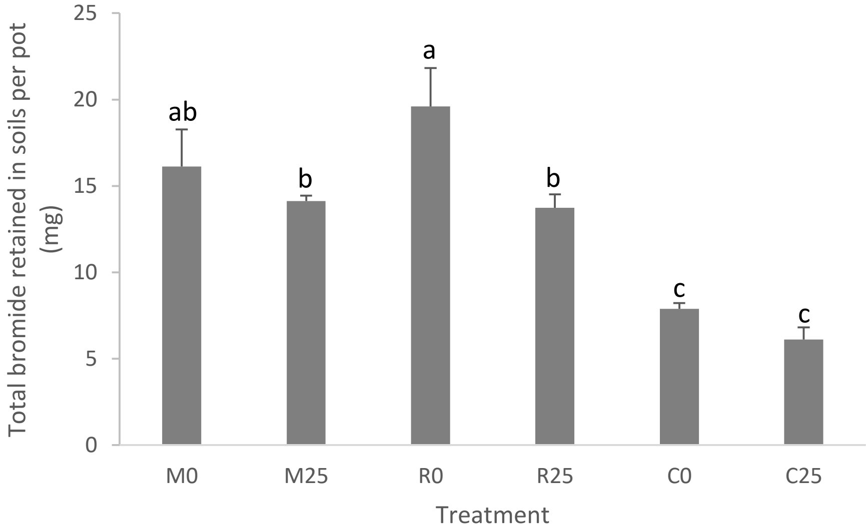


Figure 5.14. The amounts of bromide left in soils of each treatment. Error bars are standard errors. The same letters indicate no significant difference (n=3, p<0.05).

5.3.4 Total volume of leachate in nitrate and bromide experiments

Table 5.3 shows a total volume of leachate during nitrate and bromide leaching experiments. A leachate collection was conducted eight times in the nitrate leaching experiment and nine times in the bromide leaching experiment. Thus, the sums of leachate volume were higher in the bromide leaching experiment. Gravels did not have a significant influence on the volumes of leachate under all of the plant treatments. The total volumes of leachate were significantly lower at ryegrass treatments. This would be because high biomass of ryegrass roots absorbed more water from the soils.

Table 5.3. Volumes of leachate from each treatment through three times of nitrate transport and one time of bromide transport experiment. Application rates were 4 L for the nitrate experiment and 4.5 L for the bromide experiment. The same letters indicate no significant difference (n=4, P<0.05).

Treatment	Sum of leachate volume (L)				Mean (L)
	Nitrate application			Bromide application	
	First[1]	Second[1]	Third[1]		
M0	3.5	3.7	3.7	4.1	3.9[a]
M25	3.5	3.7	3.7	4.1	3.9[a]
R0	3.0	2.8	3.3	3.7	3.3[b]
R25	3.0	2.7	3.3	3.6	3.2[b]
C0	3.6	3.9	3.7	4.1	3.9[a]
C25	3.6	4.0	3.8	4.1	4.0[a]

[1]Times of the nitrate leaching experiment

5.4 Discussion

5.4.1 Comparison of nitrate and bromide leaching

Table 5.4 presents nitrate and bromide recovery rates through leachate. The nitrate recovery was 20-30 % lower than bromide under the plant treatments. This means plants reduced nitrate leaching more than bromide leaching. This agrees the previous findings that bromide and nitrate breakthrough curves had a similar location of peaks, but bromide concentration are consistantly higher than nitrate (Jiang et al., 1997; Kelly & Pomes, 1998). Clay et al. (2004) also found bromide leaching test overestimated nitrate leaching by about 25 %. According to Clay et al. (2004), bromide has a lower sorption coefficient in soils, so bromide transport is faster than nitrate. In addition, Ottman and Pope (2000) reported plant uptake and immobilization of nitrate resulted in less depth penetration of nitrate than bromide.

In the present part of the study, nitrate retained in the soils was not examined because i) nitrate was affected by plant uptake, ii) nitrate was easy to be transformed into another form of nitrogen by nitrification, denitrification, immobilization, and ammonia volatilization, and iii) the fertilizer applied before the experiment contained an additional nitrogen source which would affected the nitrate concentration in the soils. Unlike nitrate, bromide is chemically stable (Bowman, 1984) and is not an essential element for plants (Lee, 1982). However, some previous studies found bromide was also absorbed by plants. Tilahun et al. (2006) found maize absorbed 8.1 % of bromide applied in soils, and Schnabel et al. (1995) reported ryegrass could absorb 8-86 % of bromide input depending on soil drainage condition. The present study also showed the lower total bromide recovery under ryegrass (Table 5.5). It was assumed that the lower bromide in the ryegrass leachate (Figure 5.12) meant more bromide was captured in the soils. However, bromide retained in soils with ryegrass was not significantly higher than with maize (Figure 5.14). Bromide in the plants was not examined in the present study, but it appears that bromide moved into ryegrass. Ryegrass had much higher root density than maize (Figure 5.5), so the significant amount of bromide seemed to be transferred into ryegrass despite the short term of the experiment (five days). Schnabel et al. (1995) insisted bromide usage as a tracer had to be careful in long term field trials, but the present study was a short term greenhouse trial. Moreover, although the recovery rates through leachate were different between nitrate and bromide (Table 5.4), both rates agreed to i) be lowest with ryegrass and highest without plants and ii) tent to be higher at 25 % gravel soils than 0 % gravel soils under the same plant treatments. Thus, it can be concluded that the bromide transport in the present study provided the worst leaching scenario of nitrate, as concluded by Tilahun et al. (2006).

Table 5.4. Nitrate and bromide recovery rates of leachate. Percentages are against the recovery of C25.

Treatment	Recovery rate through leachate (%)	
	Nitrate	Bromide
M0	70.6	96.5
M25	76.3	97.1
R0	37.9	68.1
R25	41.0	70.0
C0	98.9	98.6
C25	100.0	100.0

Table 5.5. Bromide recovery through soils and leachate (mean ± standard error) and total recovery rates against C25.

Treatment	Bromide recovery

	In soil (mg)	In leachate (mg)	Total (mg)	Ratio (%)
M0	16.1 ± 2.2	413.9 ± 3.0	430.0	98.9
M25	14.1 ± 0.3	416.2 ± 1.5	430.3	98.9
R0	19.6 ± 2.2	292.1 ± 45.3	311.7	71.7
R25	13.7 ± 0.8	300.1 ± 29.9	313.9	72.2
C0	7.9 ± 0.3	422.8 ± 2.1	430.7	99.0
C25	6.1 ± 0.7	428.8 ± 1.8	434.9	100.0

5.4.2 Effects of gravels on plant growth

Plant shoots

Rock fragments have had different impacts on plant growth depending on plant species. The growth of Korshinsk peashrub (*Caragana korshinskii Kom.*) was hindered by rock fragments (Mi et al., 2016), but aboveground biomass of wheat was higher with the presence of rock fragments (Danalatos et al., 1995). In the present study, rock fragments only had an influence on aboveground biomass in maize (Figure 5.5). This is likely to be because maize is more sensitive to a deficit of nutrients, especially nitrogen (Ortega & Santibáñez, 2007). Nutrient status of the experimental soils was not analysed, but 25 % gravels occupied the space of soil and would result in the lower total amount of nutrients. This is supported by Novák and Kňava (2012) demonstrating gravels reduced soil nutrient holding capacity. Figure 5.14 also showed 25 % gravel soils could retain lesser amounts of nutrients than 0 % gravel soils. While a soil nutrient status, especially nitrogen, is one of the most important factors to grow maize (Pandey et al., 2000), ryegrass is less sensitive to soil fertility (Charlton & Stewart, 1999). According to Ravel et al. (1997), ryegrass is more sensitive to drought, but the present study did not have a drought problem. This would be the reason why the growth of ryegrass was not influenced by the lower nutrient capacity of 25 % gravel soils, different from maize. Thus, the effect of gravels on plant growth is concluded to depend on the characteristics of plant species. Ryegrass seems to be a better choice to grow in a stony soil than maize.

Plant roots

In the present study, gravels had no significant effect on root biomass (Figure 5.5) even though it is known that the low nutrient holding capacity of a stony soil can decrease plant biomass (Novák & Kňava, 2012; Rytter, 2012). According to van Wesemael et al. (1995), rock fragments encourage root penetration by decreasing mineral soil bulk density around rock fragments, particularly in compacted soils. In addition, preferential flows generated by rock fragments have been found to induce a nutrient pool near the flow paths, which increased root density around rock fragments (Rytter, 2012). Moreover, rock fragments may provide a favourable environment for root growth by regulating soil temperature (Du et al., 2017). Despite those positive effects of rock fragments, root density around rock fragments was not significantly higher in the present study. This may be due to the limitation of a pot-scale experiment. Firstly, repacked soils were not highly compacted, so root penetration might not be significantly restricted by mineral soils. This would mean the roots did not need to penetrate only around rock fragments, which was different to the work of van Wesemael et al. (1995) described above. Secondly, newly repacked soils may not have had enough time to create a nutrient pool around rock fragments. Furthermore, the limited nutrient supply in this experiment would not have accumulated enough nutrients in preferential pathways during the period of the experiment. Thus, the explanation of Rytter (2012) above probably cannot be applied to the present study. Unlike a study of Du et al. (2017) above, rock fragments would not significantly affect soil temperature because this experiment was conducted in a greenhouse. Poesen and Lavee (1994) pointed out that the effect of rock fragments on plants varies with the characteristics of mineral soils and the climate of the research area. To identify the more accurate relationship between rock fragments and plant roots, a future study under field condition with a long time period is required.

5.4.3 Effects of gravels on their own on nutrient leaching

Influence on solute transport

C25 shows the higher velocity of solute transport (Figure 5.7 and 5.10) and the higher amounts of solute leaching (Table 5.1 and 5.2) than those of C0. This result supports a previous investigation that rock fragments accelerated solute transport (Zhou et al., 2011). This is because gravels reduced the nutrient holding capacity of soils by occupying space for nutrient storages (Rytter, 2012) and increased continuous pores along rock-to-rock interfaces (Zhou et al., 2011). The effect of rock fragments on continuous porosity was discussed in the previous Chapter. The continuous pores generated along the surface of rock fragments remarkably increase the risk of nutrient leaching by decreasing water residence time in soils (Cichota et al., 2016; Di & Cameron, 2002).

Influence on total volumes of leachate

Water leaching is likely to be faster in C25 as discussed in the above section. However, there was no significant difference in total leachate volumes between C0 and C25 (Table 5.3). This result does not correspond to the general knowledge that soils containing rock fragments have a smaller water capacity than soils without rock fragments (Novák & Kňava, 2012), which induces an expectation of higher water leaching from 25 % soils. This result would be because of intensive and frequent water application. Intensive water application would increase soil water content nearly the level of field capacity after every single water application. Although the water holding capacity of non-stony soils is higher than stony soils, if the capacity of both of the soils is already full, the leachate volumes from both of the soils would be the same. This indicates although gravels decrease water holding capacity of soils, leachate volumes in stony soils would not always increase, depending on soil moisture levels and water management. This suggests that proper water management could decrease nutrient leaching problems in stony soils.

Potential possibility of increasing fertilizer efficiency

Under the same plant treatments, mineral soils with 25 % gravels tended to have a higher concentration of bromide (Figure 5.13). According to Poesen and Lavee (1994), fertilizer concentration is higher in mineral soils in a stony soil than a non-stony soil because the stony soil has a smaller fraction of mineral soils, but fertilizer input is the same. Nevertheless, the increased element concentration of the mineral soil could not recover the decreased nutrient holding capacity caused by gravels, so the retained bromide per each pot tended to be always higher in 0 % gravel soils (Figure 5.14). Thus, it is concluded that gravels have negative effects on nutrient leaching and fertilizer efficiency. In Eyrewell, removing all rock fragments from soils would be impossible. To reduce the negative impact of rock fragments on the environment, a future study is recommended to find a proper fertilizer input for a stony soil should be preceded with consideration of plant productivity. Rock fragment content in agricultural soils is usually ignored when fertilizer input is decided, which leads to the excessive application of fertilizer. If fertilizer input is adjusted with considering the reduced fraction of mineral soils, overall fertilizer usage would be reduced. Less use of fertilizer will eventually decrease environmental problems and give an economic benefit to farmers. As the present study demonstrated the growth of ryegrass was not affected by rock fragments, and rock fragments concentrated more nutrients in mineral soils, the future study would be worth to be conducted.

5.4.4 Effect of plant roots on their own on nutrient leaching

Effect of the existence of plant roots

M0 and R0 showed lower solute recoveries through leaching than C0 (Table 5.4). Also, M0 and R0 showed higher solute recovery in the soils than C0 (Table 5.5). This indicates plant roots helped to decrease solute leaching by increasing solute retention in the soils. This is mainly because plant roots decreased water leachates (Table 5.3) by absorbing water. The reduced water content at root-soil interfaces eventually enhances the water holding capacity of soil (Carminati et al., 2011). Because solute transport is closely related to soil water flow, the reduced water leaching can effectively decrease solute leaching. Plant roots absorb not only water but also nutrients from soils, which reduces the solute concentration of the soils. This decreases the potential loss of solutes through leachate and gives more capacity to the soil to hold nutrients.

Relationship between root density and nutrient leaching

R0 which had higher root density decreased solute leaching more effectively than M0 (Table 5.4). M0 and R0 showed the higher bromide concentration at 0-15 cm soils (Figure 5.13) where the root density was higher. This was obviously different from C0 which showed a vertically even concentration of bromide in the soil. This indicates higher root density is more beneficial to reduce nutrient leaching by capturing nutrients in soils. This is supported by previous findings. Dunbabin et al. (2003) also found that high root density in topsoils enhanced nitrate capturing. Although a deeper root zone of maize can be beneficial to capture nutrients (Thorup-Kristensen, 2006), higher root density was much more effective than longer roots to reduce nitrate leaching (Dunbabin et al., 2003). This is because root metabolic activity has a larger impact on solute leaching than root architecture (Malcolm et al, 2014). Higher root biomass is more advantageous to absorb water and nutrient within a short time, thus, the positive effect of plant roots increased with increasing root density.

Effect of root channels on generating preferential flow

Many studies have proved that plant root channels acted as preferential flow pathways (Devitt & Smith, 2002; Ghestem et al., 2011), which could enhance nutrient leaching. However, the present study did not find any evidence that plant roots increased preferential flow. Both thicker roots (maize) and high density of roots (ryegrass) reduced the solutes in leachate (Table 5.4). Actually, most previous studies on this topic are related to woody plant roots (Devitt & Smith, 2002; Johnson & Lehmann, 2006) or decayed or dead root channels (Ghestem et al., 2011; Schwärzel et al., 2012). Woody plants create large pores near the trunk, which enables to initiate preferential flow (Ghestem et al., 2011). However, the roots of maize and ryegrass are relatively finer compared to woody plants. In addition, the present study only includes living roots rather than decayed or dead roots. There is a lack of studies which compares the effect of living and dead root channels on preferential flow (Ghestem et al., 2011). In the present study, the positive effect of plant roots on decreasing leachate volumes was mostly related to the living activity of plants. Therefore, it seems that highly active living roots contributed to reducing preferential flow and nutrient leaching.

5.4.5 Combined effect of rock fragments and plant roots on nutrient leaching

C0 showed lower solute recovery through leachate than C25, however, M25 and R25 reduced more solute leaching than C0 (Table 5.4). This indicates the existence of plant roots can effectively prevent the intensive solute leaching in stony soils. Although rock fragments decrease the capacity of soils, plant roots can increase the capacity higher than that of non-stony soil. It seems that the positive effect of plant roots is larger than the negative effect of rock fragments on nutrient leaching. This implies that creating vegetation in stony soils can be greatly beneficial to reduce environmental concerns. However, as mentioned in the above section, this positive effect of plant roots is available only while the plant is alive. After plants die, dead or decayed root channels will obviously induce a different result in nutrient leaching. In Eyrewell, annual or perennial plants including ryegrass in dairy farms would continuously generate dead root channels. Thus, the combined effect of rock fragments and plant roots needs further investigation with the existence of decayed and dead root channels. This will be discussed in Chapter 5.

5.5 Conclusion

The pot experiment represented in this chapter identified the effect of rock fragments and plant roots on soil nutrient leaching by investigating root biomass, volumes of leachate, element leaching velocity, element recovery rates in soils and leachate, leading to the following conclusions:

Ⅰ. Rock fragments have different effects on plant biomass depending on plant species. The growth of ryegrass was not affected by rock fragments whereas aboveground biomass of maize was decreased in a stony soil.

Ⅱ. Rock fragments caused faster and increased rates of nutrient leaching by decreasing the nutrient holding capacity of soils.

Ⅲ. Plant roots significantly decreased the total amount of nutrient leaching by absorbing water and nutrient and capturing solutes in the adjacent soils. Ryegrass which had higher root density had a much larger influence in restricting nutrient leaching than maize.

Ⅳ. With the co-existence of rock fragments and plant roots, the positive effect of plant roots was larger than the negative effect of rock fragments in restricting nutrient leaching. Soils with plant roots effectively reduced nutrient leaching, but rock fragments decreased the capacity of soils to retain nutrients.

Ⅴ. These findings point to the requirement for further studies on the effect of decayed and dead root channels on water flow and solute transport (see Chapter 6).

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Chapter 6

Effect of rock fragment content and decayed root channels on solute transport in an unsaturated lysimeter system

6.1 Introduction

Lysimeters are often used for solute transport studies, allowing measurement of soil water moisture, water fluxes, and solute movement in a soil whilst controlling the spatial variation of soils (Abdou & Flury, 2004). Effectively, a lysimeter-scale experiment is an intermediate technique between field measurement and small-scale laboratory studies (Abdou & Flury, 2004).

Breakthrough curves of soil EC provide a valuable understanding of solute transport. By comparing the time of peaks, the location of solutes and solute residence time can be presumed (Ma & Selim, 1994). Obtaining solute breakthrough curves from a soil is not easy, but time domain reflectometry (TDR) enables to measure soil moisture and Electrical Conductivity (EC) continuously and simultaneously (Ritter et al., 2005). This technique is simple and cost-effective and allows a breakthrough curve to be obtained without laboratory analysis of solute concentration (Vanclooster et al., 1993). Moreover, TDR enables to measure soil EC at different depths with the less destruction of soils (Vanclooster et al., 1993). Thus, TDR has often been used to examine solute transport through soils, measuring EC. Risler et al. (1996) compared two breakthrough curves obtained by estimating leachate EC using TDR and analysing the solute concentration in the leachate. Two breakthrough curves corresponded well, which indicated TDR can be successfully used to obtain breakthrough curves. Nadler et al. (1991) proposed that TDR could also be used to investigate solute transport in soils. Research reported in this chapter as the objective to investigate the effect of rock fragment content and dead or decayed root channels on solute transport using a lysimeter fitted with TDR.

6.2 Material and methods

6.2.1 Description of lysimeter system

Repacked lysimeters and TDR recording system were located at Plant & Food Research (PNF), Lincoln a Crown Research Institute (CRI) of New Zealand. Lysimeters in a field site at PNF (90 cm in height and 30 cm in diameter) had been previously filled with 0 %, 30 %, and 50 % stony soils. The lysimeters were located in the center of the square plot with a surrounding of buffer areas (Figure

6.1a). Time domain reflectometry (TDR) sensors (CS6) had been installed horizontally (Figure 6.1b) at four different depths (75, 225, 375 and 525 mm), and information of volumetric water content (VWC), EC, and soil temperature were regularly recorded. The TDR data were automatically saved in a connected computing system as a 'dat' file. The sensors were calibrated with the stony soils before installation, and their reading was automatically corrected following the calibration. Leachate collecting systems were also placed at the bottom of the lysimeters (white boxes in Figure 6.1a). The lysimeters were set up and filled approximately 4 years prior to the current experimental work. Previously, PFR had grown wheat in these lysimeters for other research projects. Aboveground parts of the crops were removed, but underground parts were left intactly. After the most recent shoot harvest (January 2017), irrigation was stopped. Therefore, it was likely that root channels still existed in each soil, thus, providing a reasonably realistic reflection of an agricultural plot at the start of the experiment.

There were a total of twenty-four lysimeters with six treatments and four replicates, but the present study used nine lysimeters with three treatments as described in Figure 6.2. Three replicates out of four were used for bromide transport experiment, and the other one was used for a preliminary test. Each lysimeter had stony soils above a gravel layer at the bottom. The TDR sensors were not installed at the gravel layer. In Figure 6.2, abbreviations refer to the depth of TDR sensors, rock fragment content, and repetition.

(a)

(b)

Figure 6.1. A lysimeter system in Plant&Food Research in Lincoln; (a) lysimeters located in the center of buffet areas and leachate collecting systems, (b) TDR installation in the lysimeter.

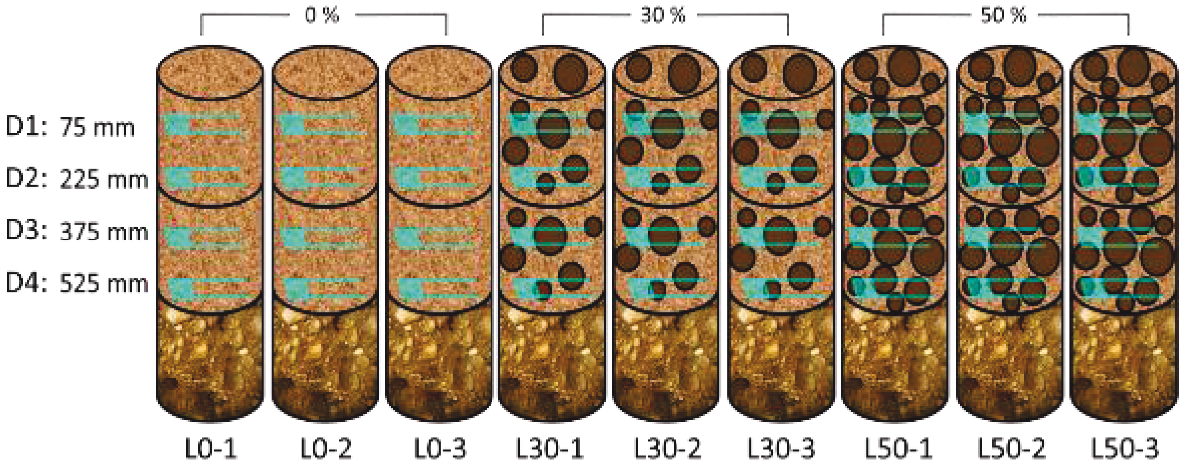

Figure 6.2. Description of the lysimeters used in the present study and abbreviations for each lysimeter and the depth of TDR sensors. D1-D4 refers to each depth of TDR. L0, L30, and L50 refer to 0 %, 30 %, and 50 % stony soils, respectively, and the numbers after hyphen refer to a replicate.

6.2.2 TDR EC readings without applying bromide

The soils in the lysimeters used for a bromide transport experiment were washed out to eliminate background solutes by applying 2 L of water 2-3 times a day for two weeks. Leachate EC decreased after washing out the soils as showed in Table 6.1, which was considered likely to have largely eliminated the impact of background solutes from the bromide transport experiment.

Soil EC readings using TDR can be affected by soil moisture and temperature. When soil water content increases, soil EC also increases without an increase in solute concentration because soil moisture influences transient condition. This is one of the concerns in a solute transport study using TDR. Solute transport tests need to apply water continuously, so soil moisture consequentially increases. Although solutes do not reach a deep soil, the EC of the deep soil can increase because of soil water. To judge whether an EC increase in a bromide transport test was caused by bromide or water, soil EC reaction against pure water was investigated prior to the actual test of bromide transport. Water was applied twice between April 12th and 15th and there was no bromide application. Soil EC and VWC were measured using TDR. After the bromide transport test, the soil EC peaks in this test were compared to the EC peak of the bromide transport test. When the EC peak in the bromide transport test was higher than the peaks of this test, it was judged that bromide caused the EC increase. Soil VWC changes were similar in those two tests, which supported this judgment.

The effect of soil temperature was ignored in the present study because the bromide transport experiment lasted only 2.5 hours, so soil temperature was assumed to be constant. TDR readings of this test were compared

Table 6.1. Leachate EC before and after washing out soils in each lysimeter (μS cm^{-1}).

	L0-1	L0-2	L0-3	L30-1	L30-2	L30-3	L50-1	L50-2	L50-3
Before washing out	1132	923	930	659	627	756	447	570	650
After washing out	416	449	445	280	211	438	227	185	162

6.2.3 Bromide transport experiment

A bromide transport experiment was carried out between April 18th and 22nd in 2017. Vegetation on the surface of each lysimeter was removed by hand. Tap water (1 L) was applied to each lysimeter every 6 minutes. After the third application, 20 g of KBr powder (13.4 g Br) was evenly scattered on a surface of soils. The water application then continued for 2.5 hours; the total amount of applied water was 27 L. TDR sensors recorded soil EC and VWC every 3 minutes. Leachate from each lysimeter was collected, and leachate EC and volumes were measured every 6 minutes using a portable EC meter (ExStik EC 400, EXTECH Instruments) and a volumetric cylinder, respectively. The amount of bromide in the leachate was calculated as described in Chapter 5.2.3. TDR data was analysed using Jupyter (IPython), and leachate data were analysed using Fisher's one-way ANOVA using Minitab 18.

6.3 Results

6.3.1 Total amount of leached bromide and leachate

Table 6.2 presents the total amounts of leached bromide and total leachate volumes in each lysimeter. The leached bromide was highest in L50 and lowest in L0 despite no significant difference in the total volumes of leachate. This indicates higher rock fragment content is more vulnerable to nutrient leaching.

Table 6.2. The total amounts of leached bromide and volumes of leachate. Recovery rates are ratio of leached bromide against bromide input. The same letters indicate no significant difference.

Treatment	Leached bromide			Leachate	
	Total amount (g)	Mean (g)	Recovery (%)	Total volume (L)	Mean (L)
L0-1	3.74			20.1	
L0-2	2.27	2.59[b]	19.3	18.8	19.8[a]
L0-3	1.77			20.5	
L30-1	5.08			20.7	
L30-2	3.59	3.76[ab]	28.1	20.3	20.5[a]
L30-3	2.62			20.5	
L50-1	5.96			21.1	
L50-2	5.48	5.60[a]	41.8	19.7	20.6[a]
L50-3	5.37			21.1	

6.3.2 Assessment of soil EC peaks

Soil EC changes with and without bromide are shown in Appendix A. By comparing the heights of the EC peaks, the soil EC increases in a bromide transport experiment were judged whether they were caused by bromide or soil moisture and summarised in Table 6.2. The observation of soil EC peaks was limited within 2.5 hours.

Table 6.3. Summary of the judgement whether soil EC increases caused by bromide or not in each experimental lysimeter (see Figures A.1a-A.9a).

Treatment	Judgement of soil EC increases
L0-1	There was no soil EC increase caused by bromide.
L0-2	There was no soil EC increase caused by bromide.
L0-3	Only D1 showed an EC increase caused by bromide and appeared within 2.5 hours.
L30-1	Soil EC at D1, D2, and D3 increased by bromide, but the EC peaks appeared after 2.5 hours.
L30-2	Soil EC increased by bromide at all depths, but only D1 and D2 showed the EC peaks within 2.5 hours.
L30-3	Soil EC increased by bromide at all depths, and every peak appeared within 2.5 hours.
L50-1	Soil EC increased by bromide at all depths, and every peak appeared within 2.5 hours.
L50-2	Soil EC increased by bromide at all depths, and every peak appeared within 2.5 hours.
L50-3	Soil EC increased by bromide at all depths, and every peak appeared within 2.5 hours.

In each lysimeter, five EC breakthrough curves were obtained; four of them were from four depths of soil, and the other one was from leachate. All breakthrough curves are shown in Appendix A. Figure 6.3 presents when the peaks of the breakthrough curves appeared in each lysimeter. D1, D2, D3, and D4 are soil EC peaks at each depth, and LC is a leachate EC peak. Three replicates of L0 rarely showed the soil EC peak, which implies most bromides was still in the soils shallower than D1. The occurrence of soil EC peaks became more frequent with increasing rock fragment content. Bromide passed all depths of the soil in one replicate of L30 and all of L50. This indicated that bromide transport became faster with increasing rock fragment content.

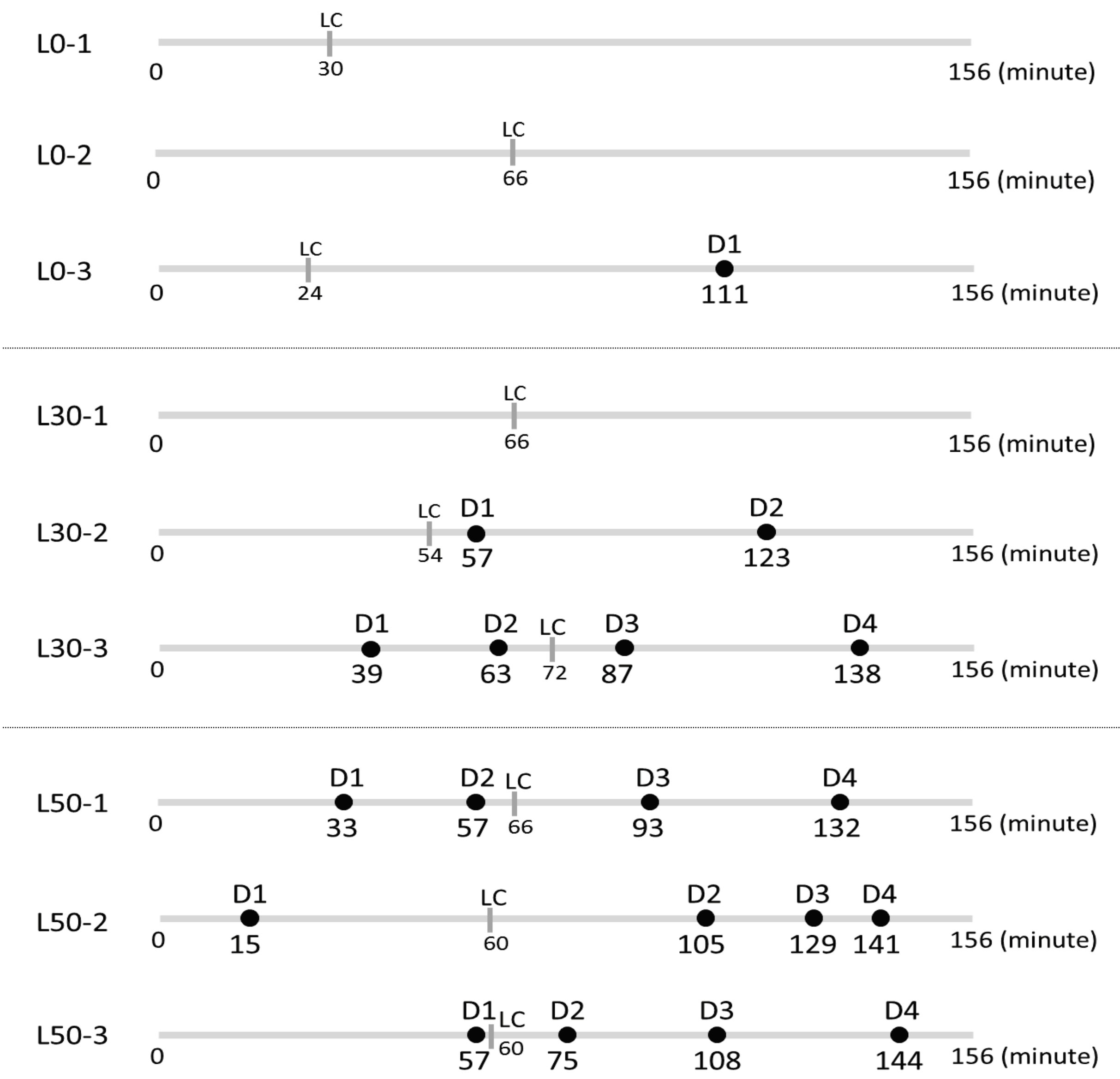

Figure 6.3. EC peak occurrence in each lysimeter after bromide application. D1, D2, D3, and D4 are soil EC peaks at different depths, and LC is a leachate EC peak. Numbers are the time of EC peak appeared. Soil EC peaks at deep soils appeared more frequently with increasing rock fragments, which indicates rock fragments accelerated solute transport.

6.4 Discussion

6.4.1 Two domains of solute transport

Theoretically, it was expected that EC peaks appeared in the order of 'D1 - D2 - D3 - D4 - leachate' followed the downward movement of bromide. However, in every lysimeter, leachate EC peaks appeared earlier than D3 and D4 (Figure 6.3). Moreover, L0-1, L0-2, and L30-1 had no soil EC peaks at all, but their leachate EC had peaks. This strongly indicates that a certain early and rapid bromide leaching occurred without affecting soil EC. This early solute leaching has been usually observed in the previous solute transport research. Many studies have reported double peaks in breakthrough curves of leachate (Ma & Selim, 1994; Skopp et al., 1981; Strock et al., 2001). According to Ghestem et al. (2011), soil water flow has two domains in the soil, i) gradual uniform flow through fine pores and ii) preferential flow through single or interconnected macropores. The second peak of the double peaks in the previous study was caused by normal solute movement through the gradual flow, and the first peak was generated by the preferential flow. The leachate EC peaks in the present study seem to be similar to the first peak because they were faster than soil EC peaks. There was no second peak in the present study, probably because of a short experimental period. The second peaks may appear if the experiment lasted longer.

From this result, two domains of bromide transportation can be recognized as illustrated in Figure 6.4. Gradual transport (GT) is a normal solute transport through uniform water flow, and Early transport (ET) is rapid leaching through preferential flow. Table 6.4 summarizes the characteristics of each transport. In the present study, GT can be estimated by comparing soil EC peaks, and ET can be compared by leachate EC peaks. Each domain is differently related to nutrient leaching, so the effect of rock fragments on each domain of solute transport needs to be discussed respectively.

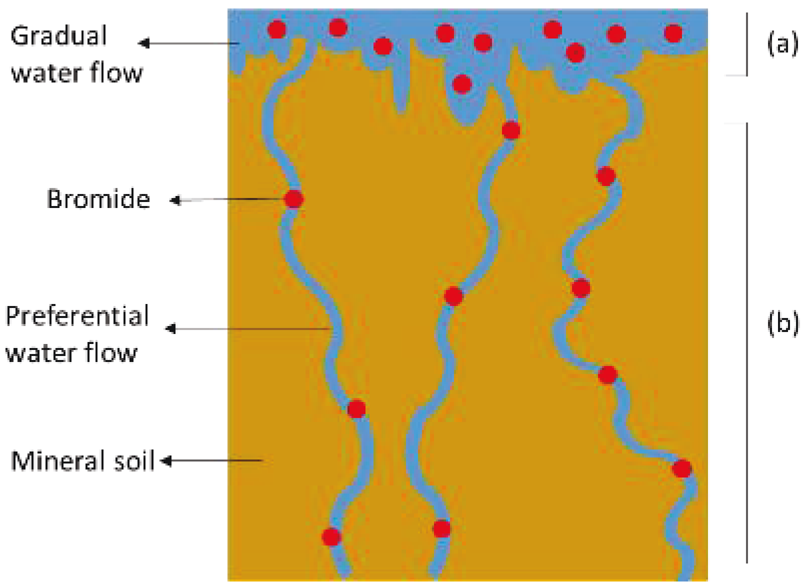

Figure 6.4. Illustration of two domains of water flow and bromide transports at an early stage of water irrigation in unsaturated soil; (a) Gradual transport (GT) by uniform water flow through fine pores and (b) Early transport (ET) by preferential flow through macropores.

Table 6.4. Description of two domains of bromide transport.

Solute transport	Description
Gradual transport (GT)	- This is a normal solute transport through soils. - This transport is indicated by the soil EC peaks in the present study. - The velocity of GT can be analysed by comparing the time of soil EC peaks at each depth. - This transport is highly influenced by the characteristic of soil.
Early transport (ET)	- This is early solute leaching caused by preferential flow. - This transport is indicated by the leachate EC peaks in the present study. - The velocity and intensity of ET can be analysed by comparing the time and height of leachate EC peaks. - This transport is highly related to early preferential flow.

6.4.2 Effect of rock fragments on Gradual transport (GT)

Soil EC peaks in Figure 6.3 show that rock fragments accelerate bromide transport through GT. This agrees to the previous findings that rock fragments enhanced the downward movement of solutes (Zhou et al., 2011). This is mainly due to the reduced nutrient holding capacity of stony soil (Rytter, 2012). Although bromide is a negatively charged element, soils still enable to capture bromide by absorbing in soil organic matter (Strock et al., 2001). Rock fragments take a space instead of mineral soils, thus, the total amount of organic matter is lower in a stony soil. Therefore, stony soils have a lower holding force to capture solutes, which results in a faster solute movement. In addition, the mineral soils around rock fragments are looser than the other part of the soil (Khetdan et al., 2017). Increasing rock fragment content increases looser mineral soils, which enhances water flow rates. Therefore, rock fragments enhance solute transport through GT.

6.4.3 Effect of rock fragments on Early transport (ET)

The velocity of bromide leaching through ET

Most leachate peaks of L0 were faster than L30 and L50 (Figure 6.3), which indicates rock fragments had a delaying effect on bromide leaching through ET. In the present study, the lysimeters contained dead or decayed root channels resulted from the previous research of PNF. These root channels are open, continuous, and larger than other soil pores (Devitt & Smith, 2002; Ghestem et al., 2011; Mitchell et al., 1995), so solutes are preferentially moved through decayed root channels (Li & Ghodrati, 1994). As simply illustrated in Figure 6.5, root growth in L0 would have no obstacle, however, increasing rock fragment content disturbs root penetration, resulting in increasing tortuosity of root channels. This result is consistent with the finding of Chapter 3 in that rock fragments interfered rapid preferential flow (see Figure 3.20). Consequently, bromide leaching through the root channels becomes slower with increasing rock fragments. However, in L50, high content of rock fragments increases the contact between rock fragments and creates continuous rock-to-rock pores along their surface (Beibei et al., 2009), as reported in Chapter 4. This generates additional preferential flow paths, so bromide transport through ET is enhanced. This would be the reason why the leachate EC peaks of L50 were not faster than L30. Although L50 had the higher tortuosity of root channels than L30, there were more numbers of preferential pathways in L50 due to the high volume of rock fragments. Therefore, under the existence of dead or decayed root channels, 30 % of rock fragment content is optimum to decrease the velocity of bromide leaching through ET.

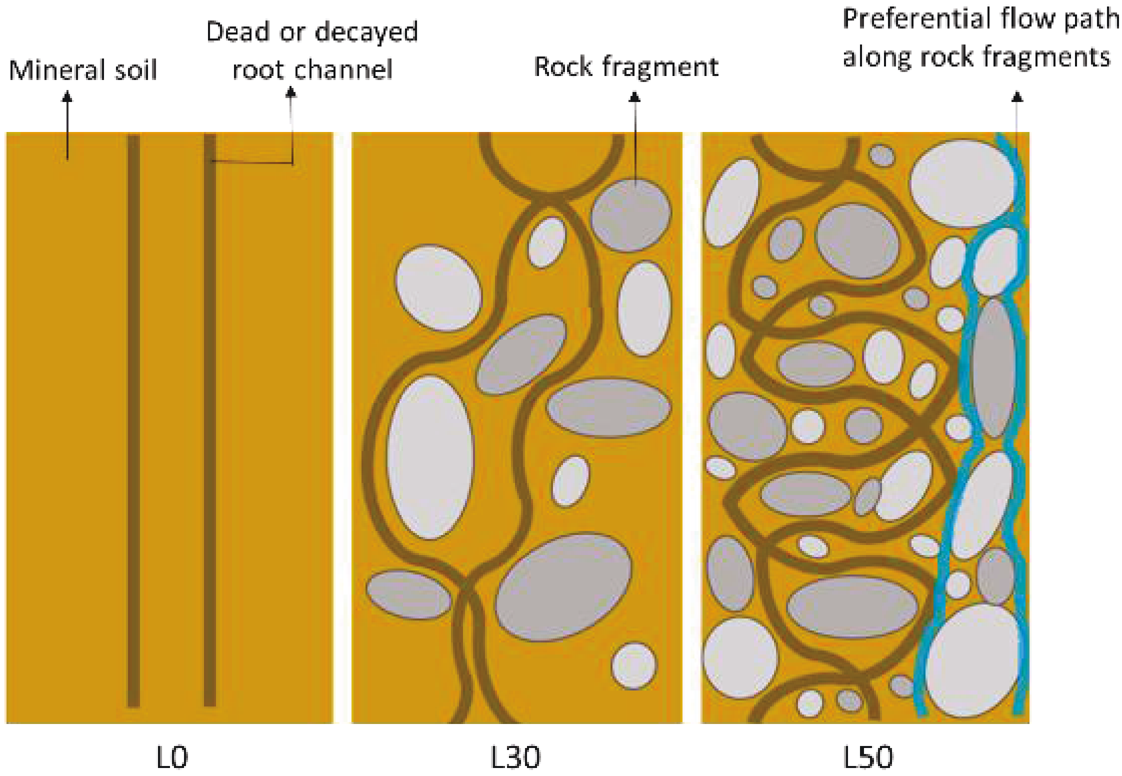

Figure 6.5. Hypothetical illustration of dead or decayed root channels in each stony soil. Increasing rock fragment content increases the tortuosity of root channels, which decreases the velocity of solute transport through the root channels. However, high content of rock fragment in L50 generates additional preferential flow pathways along the contacted surface of rock fragments, which enhances solute transport.

The intensity of bromide leaching through ET

Figure 6.6 shows the location of the leachate EC peaks of each lysimeter. The time of leachate peaks indicates the velocity of ET, and the height of the peaks indicates the intensity of bromide leaching at the peak. The heights of early peaks (L0-1 and L0-3) were higher than most of the other peaks. This is because the velocity of solute transport is closely related to the intensity of solute leaching. Solute leaching through a faster flow is more intensive than a slower flow because solutes had only a limited time to contact with soil particles. Rock fragment content also influences the intensity of bromide leaching through ET. Among the seven peaks which appeared between 50-80 minutes, the peaks of L50 tended to be higher than L0 and L30. This indicates when the velocity of ET is similar, increasing rock fragment content increases the intensity of solute leaching. This would be because of the lower holding capacity of a highly stony soil. The intensity of ET is associated with environmental problems. If the same amount of nitrate is leached, intensive leaching within a short time would be more risky to the environment than a low concentrated leaching for a longer time. In Table 6.2, the sums of bromide leaching of L0-1 and L0-3 were lower than other treatments, however, in Figure 6.6, their leaching intensity were higher than most of the others. This implies that L0 could not be the best option for agricultural soil in spite of the highest holding capacity of the soil.

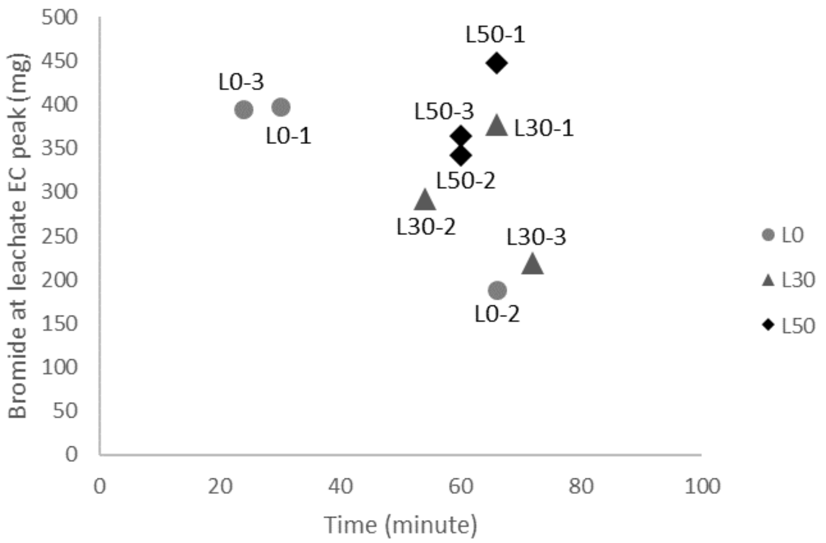

Figure 6.6. Locations of leachate EC peaks of each lysimeter. The time of each peak appeared indicates the velocity of bromide transport, and the height of each peak indicates the intensity of bromide leaching. The intensity of rapid peaks (L0-1 and L0-3) were higher than most of the other peaks.

6.4.4 Optimum rock fragment content to reduce solute transport

In summary, under the existence of dead or decayed root channels, rock fragments had different impacts on two domains of solute transport. This is summarized in Table 6.5. Overall, L30 was likely to be the most acceptable for an agricultural soil. L0 was the best in terms of GT, but L0 had a high possibility of rapid and intensive leaching through ET. L50 was not favourable for agricultural soil because the low holding capacity of the soil resulted in fast and high leaching through both GT and ET. L30 effectively decreased solute leaching through ET. In terms of GT, L30 showed intermediate flow averagely, but three replicates of L30 had a high variation (see Figure 6.3). This would be because the effect of intermediate rock fragments is highly affected by the distribution and alignment of rock fragments as reported in Chapter 4 (see Chapter 4.4.2). Moreover, according to Su (2001), a minor change in soil properties can have a huge impact on solute transport, particularly under the unsaturated condition. Also, Strock et al. (2001) pointed out that the spatial and temporal variability of soils induced highly complexed solute transport. Therefore, further study on reducing the variation of the effect of intermediate rock fragment content would be highly valuable.

Table 6.5. Overall characteristics of solute transport in each stony soil.

Treatment	GT	ET
L0	Slow	Rapid and highly intensive
L30	Intermediate	Slow and less intensive
L50	Fast	Slow and highly intensive

6.5 Conclusion

Ⅰ. Solute transport in a stony soil with the existence of dead or decayed root channels had two domains, Gradual transport (GT) which was a uniform solute transport through fine pores and Early transport (ET) which was rapid solute leaching through macropore preferential flow.

Ⅱ. Dead or decayed root channels were major preferential flow pathways which highly influenced solute leaching through ET.

Ⅲ. GT was accelerated by increasing rock fragments because rock fragments reduced the holding capacity of the soil by taking a space instead of mineral soils.

Ⅳ. Rock fragments delayed solute transport through dead or decayed root channels by increasing tortuosity of those channels. However, high rock fragment content created additional preferential flow paths which enhanced solute leaching through ET.

Ⅴ. Soils with 0 % and 50 % rock fragments had obvious disadvantages. Soils with 0 % rock fragments were vulnerable to solute leaching through dead or decayed root channels. Soils with 50 % rock fragments resulted in rapid and intensive solute transport through both GT and ET.

Ⅵ. Soils with 30 % rock fragment were found to be optimum for these soils in terms of decreasing solute transport through ET and the moderate risk of GT. However, the effect of 30 % rock fragments on GT was variable depending on the distribution and alignment of rock fragments. This provided a further complicating factor to solute transport mechanisms. Further research on this topic would be worthwhile.

Chapter 7

Effect of rock fragments on soil water flow, in-situ at Te Whenua Hou

7.1 Introduction

In previous chapters, the effects of rock fragment on soil water flow and solute transport were investigated at a laboratory-, pot-, and lysimeter-scale. Before applying the findings of these trials to the field, an investigation is required to understand how in-situ field conditions differ. The relationship between rock fragment content and tension infiltration rates requires investigation to fully understand the role of rock fragments in the field. Regional soil hydraulic properties are difficult to estimate due to the heterogeneity of field soils (Tetegan et al., 2012), but spatial variation needs to be understood to achieve efficient and optimal soil usage and management (Or & Hanks, 1992). More site-specific studies of the effect of rock fragments on soil hydraulic properties are required (Ma et al., 2010). The current part of the present study aims to identify the overall effect of rock fragment content on other soil properties and soil water flow at the Te Whenua Hou site using a tension infiltrometer in-situ. The relationships between rock fragments and adjacent soil properties are also evaluated.

7.2 Materials and Methods

7.2.1 Site information

The location of the experimental area of Eyrewell was in a farm margin and a pine forest described in Chapter 3.2.1. The ground surfaces at these sites were mostly covered by grasses, mosses, and herbs. Twelve measurement sites were selected, avoiding nearby trees to minimize the effect of thick plant roots on the results.

7.2.2 Field infiltration measurement

A tension infiltrometer used in this part of the study Figure 7.1. To improve the contact between the soil surface and the base disc, vegetation of each measurement site was removed using a small shovel and a putty knife. Soil surfaces were carefully flattened to minimize the disturbance on the soils. Infiltration rates were measured with four different tensions, 13 cm, 10 cm, 6 cm, and 3 cm. Detailed procedures were described in Chapter 4.2.7. The water level in the main tube was recorded every 5 minutes, and the longest time of measurement for each tension was limited to 1 hour.

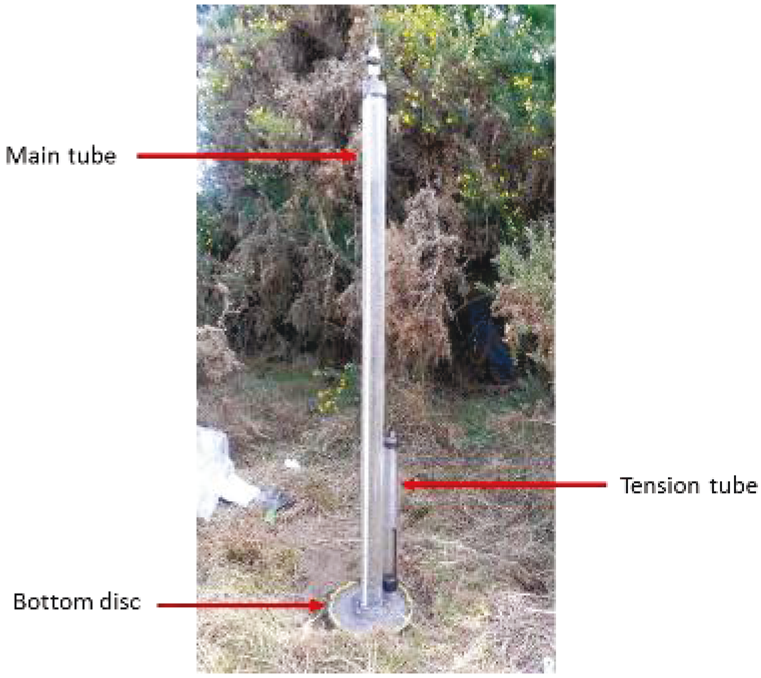

Figure 7.1. The tension infiltrometer used for the present study. A base disc was 20 cm in diameter, and a main tube was 5 cm in diameter and 1 m in length.

7.2.3 Soil collection and analysis

After the infiltration test was completed, soil beneath the infiltrometer was collected using a small shovel and a sharpened steel knife. Volume sampled was 400 cm^3 (20 cm in width X 20 cm in length X 10 cm in depth). The soils were dried in a drying oven at 30 ℃ for three days. The dried soils were sieved with a 2 mm sieve to separate rock fragments from mineral soils. A detailed procedure is described in 3.2.4.

Rock fragment contents

Volumetric rock fragment content was caculated as described in 3.2.4.

Soil particle content and organic matter

Soil particle content (sand, silt, and clay) and organic matter content was analysed as described in 3.2.5 and 3.2.7.

Mineral soil bulk density

Mineral soil bulk density was calculated as described in 3.2.6.

Plant roots

Plant roots in the oven dried soil samples were carefully separated and weighed.

7.2.4 Potential infiltration rates

The surface of Eyrewell soils appeared to have water repellency which it was thought may have a considerable impact on water infiltration rates (see Figure 1.3). Infiltration rates are generally considered to reflect continuous porosity but, in water-repellent soils, water infiltration rates significantly decrease. To estimate the actual amount of continuous pores, 'potential infiltration rates' were calculated using the measured infiltration rates and repellency index (Wallis et al., 1991). The repellency index is the ratio of the intrinsic sorptivity of ethanol against that of water (Tillman et al., 1989). In highly water-repellent soils, ethanol infiltration rates would be more accurate to estimate continuous porosity. However, ethanol is more costly than water, and using ethanol in a field has to be minimize due to environmental concerns. Instead, ethanol infiltration rates can be obtained by multiplying water infiltration rates with repellency index (Wallis et al., 1991). To obtain repellency index, a small investigation was carried out, which is described in Appendix B. The estimated ethanol infiltration rates using repellency index will be referred to 'potential infiltration rates' in the present study. The potential infiltration rates can be also considered to water infiltration rates if a soil is non-repellent. Pore diameters related to each tension were presented in Chapter 4.2.7 (see Table 4.3).

7.2.5 Statistical analysis

Pearson correlation analysis was carried out to examine linear relationships among rock fragments and soil properties using Minitab 18. The relationship between potential infiltration rates and all soil properties was analysed using forward stepwise multiple regression (Minitab 18). Variance inflation factor (VIF) was conducted to examine the multicollinearity among variables. The VIF values were smaller than 3, which indicates there was no multicollinearity problem. F value, adjusted coefficient of determination (adj-R^2), and P value of a regression equation were calculated. The normality and homoscedasticity of residuals were examined using Shapiro-Wilk test and White test, respectively (Stata SE 13). All regression residuals were normally distributed and constantly varied (homoscedasticity).

7.3 Results

7.3.1 Soil properties

Table 7.1 shows the soil properties at each experimental location. The twelve sampled locations showed a variation in soil properties even though they were closely located and appeared to be similar. The largest differences between samples were in terms of rock fragment content, organic matters, and plant root biomass.

Table 7.1. Soil properties of each sample locations at the experimental site. Maximum and minimum are shown in bold font.

Site	Rock fragment	Sand	Silt	Clay	OM[1]	MBD[2]	Plant root
	% by volume	--------------------% by weight--------------------				g cm^{-3}	g
1	9.9	**32.7**	56.6	10.7	**13.4**	0.9	**54.0**
2	2.8	27.5	60.8	11.8	7.9	1.0	7.6
3	5.0	**24.1**	60.9	15.0	7.5	**1.3**	31.0
4	2.9	30.5	59.6	9.9	8.4	1.0	37.7
5	**36.9**	27.5	58.6	13.8	9.8	**0.8**	44.0
6	3.0	28.9	59.0	12.1	7.4	1.0	81.0
7	**0.6**	27.3	**55.9**	**16.8**	**5.6**	1.1	14.0
8	13.4	30.7	58.9	10.3	8.1	0.9	12.7
9	22.9	31.5	56.5	12.1	11.2	0.9	16.0
10	12.2	28.9	**61.7**	**9.4**	8.5	0.8	**5.4**
11	15.3	30.8	57.7	11.5	9.6	1.0	20.0
12	7.8	29.7	60.4	9.8	8.4	0.9	16.9

[1]Organic matter content
[2]Mineral soil bulk density

7.3.2 Potential infiltration rates

Table 7.2 presents measured and potential water infiltration rates under four different tensions in each location. The measured infiltration rates did not always increase with decreasing tensions, which was because of water repellency. However, the potential infiltration rates corrected this problem, showing a normal gradual increase with decreasing tensions. The potential infiltration rates were used for the rest of the analysis in the present chapter.

Table 7.2. Measured and potential infiltration rates in each site. The measured infiltration rates are raw data from a field, and the potential infiltration rates are calculated values using repellnecy index (Appendix B) and the measured infiltration rates. The potential infiltration rates are more accurate to estimate continuous porosity in Eyrewell soils because of water-repellency.

Site	Measured infiltration rate (mm min^{-1})				Potential infiltration rate (mm min^{-1})			
	13 cm	10 cm	6 cm	3 cm	13 cm	10 cm	6 cm	3 cm
1	0.02	0.01	0.04	0.07	0.35	0.74	4.43	11.78
2	<0.01	<0.01	<0.01	0.01	0.03	0.24	0.31	1.54
3	0.08	0.05	0.04	0.05	1.12	2.95	4.12	8.18
4	<0.01	<0.01	0.01	0.01	0.01	0.23	0.62	1.64
5	0.02	0.02	0.02	0.02	0.29	1.13	1.86	2.54
6	<0.01	<0.01	<0.01	0.01	<0.01	0.07	0.24	2.29
7	0.04	0.07	0.05	0.05	0.58	3.74	4.95	7.53
8	<0.01	<0.01	<0.01	0.01	0.03	0.08	0.31	1.15
9	0.02	0.02	0.02	0.02	0.29	0.91	1.65	3.27
10	<0.01	<0.01	<0.01	0.01	<0.01	0.23	0.41	1.64
11	0.03	0.03	0.03	0.03	0.43	1.70	3.09	4.91
12	<0.01	<0.01	<0.01	0.01	<0.01	0.17	0.29	1.64

7.3.3

7.3.4 Relationship between rock fragments and infiltration rates

Figure 7.2 shows relationships between rock fragment content and potential infiltration rates. There was no significant linear relationship between them under all the tensions.

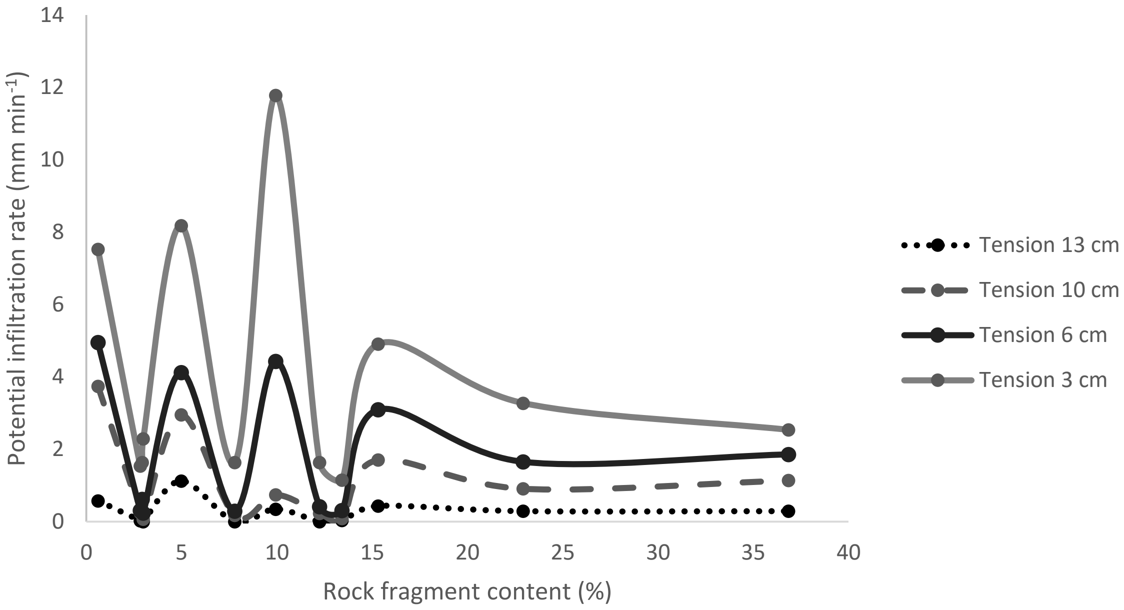

Figure 7.2. Relationships between rock fragment content and potential infiltration rates. Each tension is related to different sizes of continuous pores (see Table 4.3). Rock fragments and continuous porosity had no linear relationship regardless of pore sizes.

7.3.5 Multiple regression models

Table 7.3 shows the result of a multiple regression test between potential infiltration rates and soil properties. Related pore diameters were calculated as described in Chapter 4.2.7. The equations informed which soil property was related to infiltration rates. Rock fragment content was negatively associated with continuous porosity ≤ 0.05 cm, having a combined effect with clays and organic matter content. However, the rock fragment content did not have an influence on the infiltration rates under the other tensions.

Table 7.3. Forward stepwise multiple linear regression models for each tension infiltration rates.

Tension (related pore diameter)	Regression equation[1]	Adjusted R^2	F value	P value
13 cm (≤ 0.023 cm)	-2 - 0.04 Sand + 0.06 Clay + 0.12 OM + 1.75 MBD - 0.003 PR	0.88	17.71	0.002
10 cm (≤ 0.03 cm)	-8.25 + 0.4 Clay + 0.16 OM + 3.53 MBD - 0.02 PR	0.85	16.44	0.001
6 cm (≤ 0.05 cm)	-12.58 - 0.07 RC + 0.78 Clay + 0.67 OM	0.70	9.21	0.006
3 cm (≤ 0.1 cm)	9.4 - 0.56 Silt + 1.11 OM + 18.19 MBD	0.53	5.07	0.029

[1]OM: organic matter (%); MBD: mineral soil bulk density (g cm^{-3}); PR: plant root (g); RC: rock fragment content (%)

7.3.6 Correlation between soil properties

Rock fragment content did not have any significant correlation with the other soil properties (Table 7.4). This indicates rock fragments in Eyrewell soils had no significant impact on the adjacent soil properties.

Table 7.4. Pearson correlation between rock fragment content and other soil properties. No significant correlation was found.

	Rock fragment content (%)	
	Coefficient	P value
Sand (%)	0.17	0.60
Silt (%)	-0.20	0.54
Clay (%)	-0.01	0.98
Organic matter (%)	0.50	0.10
Mineral soil bulk density (g cm^{-3})	-0.55	0.07
Plant root biomass (g)	-0.01	0.97

7.4 Discussion

7.4.1 Rock fragment studies in a laboratory and a field

Rock fragments were negatively related to the infiltration rates at tension 6 cm, having a combined effect with clay and organic matter content (Table 7.3). However, rock fragments on their own were not related to in-situ infiltration rates (Figure 7.2). This is not consistent to the result of Chapter 4 which found rock fragment content had a strong negative relationship with infiltration rates at tension 10 cm, 6 cm, and 3 cm (see Figure 4.14). Other research on stony soils has found disagreement between laboratory and field investigations; a lot of field research has reported no significant relation between rock fragment content and water flow (Khetdan et al., 2017; X. Y. Li et al., 2008; Sauer & Logsdon, 2002). Unlike laboratory trials, Verbist et al. (2009) found a significant positive relationship between rock fragment content and tension infiltration rates, but this relationship was weak, showing a correlation efficient lower than 0.5. This is because soil water flow in the field is associated with more various factors apart from rock fragment content. Laboratory trials can control experimental conditions, so all the other factors except rock fragment content can be maintained identically. However, field soils have highly special variability as shown in Table 7.1, which indicates the effect of rock fragments on in-situ water flow could be more complicated as described in Figure 7.3.

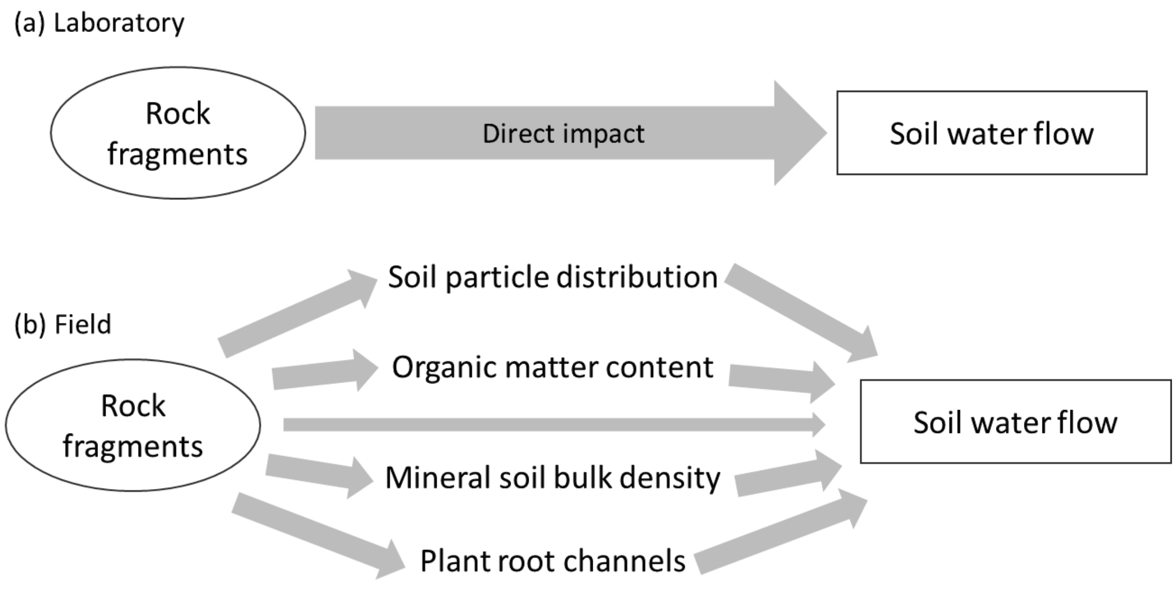

Figure 7.3. Comparison of the effect of rock fragments on soil water flow in a laboratory and in a field; (a) the sole influence of rock fragments in a laboratory, and (b) the complex influence of rock fragments in the field.

7.4.2 Relationship between rock fragments and other soil properties

Soil particle content

Sand, silt, and clay content were not related to rock fragment content (Table 7.4). This is in contrast to the finding of Sauer and Logsdon (2002) which found a strong negative relationship between rock fragments and silt and clay content. They collected soils from various regions, so they had a wider range of silt content from 10 % to 70 %, which allowed inducing more distinctive relationships. Apart from this, they used silt and clay percentages by weight against whole soil samples including rock fragments and mineral soils. When the volume of each soil sample was fixed, increasing rock fragment content naturally decreased silt and clay content, which resulted in the negative relationships in their study. However, in the present study, the content of each soil particle was a proportion against only mineral soils, so those values were more related to soil particle distribution. Thus, this is more likely to be a correlation between rock fragments and soil texture. Rock fragments are products of a weathering process, thus, rock fragment and soil particle content had no linear relationship.

Mineral soil bulk denstiy

Many studies have reported the negative relationship between rock fragment content and mineral soil bulk density in a field soil (Du et al., 2017; Khetdan et al., 2017; Rücknagel et al., 2013; Stewart, V. I., Adams, W. A., abdulla, 1975; Torri et al., 1994; van Wesemael et al., 1995). Poesen and Lavee (1994) suggested that insufficient mineral soils resulted in large gaps between rock fragments, which decreased bulk density around rock fragments. Differently, Stewart et al. (1975) reported that the interface of coarser-to-finer particles was always larger than that of finer-to-finer particles in a binary mixture. This resulted in looser soils around rock fragments, so increasing rock fragments decreased overall compaction of soils (Khetdan et al., 2017). The present study also found no significant relationship between rock fragments and mineral soil bulk density (Table 7.4). This would be because of the anthropogenic soil disturbance during soil conversion. The disturbance included tilling and leveling, so final soil bulk density seemed to be more related to the degree of leveling, rather than rock fragment content. Moreover, the random movement of heavy machinery could induce a spatial difference in the degree of soil compaction. The collected soil samples were surface 10 cm soils, so their mineral soil bulk density would be more directly affected by those artificial factors.

Soil organic matter

Previously, Qin et al. (2015) found rock fragments decreased organic matter content, but Cerdà (2001) reported a positive relationship between them. The effect of rock fragments on organic matter content has been found to vary. For example, rock fragments are concerned with microbial and enzyme activity by altering soil moisture and temperature, which was important for decomposition of organic matters (Certini et al., 2004; Tripathy et al., 2014; Wu et al., 2012). According to van Wesemael et al. (1995), rock fragments concentrated irrigated water and fertilizer in mineral soils by reducing space for flow, which increased organic matter accumulation in the mineral soils. However, in the present study, rock fragment content was not significantly related to organic matter content (Table 7.4). This seems to be related to the soil conversion, Eyrewell climate, and soil management. Soil mixing during the conversion would disturb the spatial difference in organic matter content near rock fragments. After the conversion, there was no fertilizer or organic matter input in the experimental site. In addition, soils were dry due to the dry weather. Under these conditions, the degradation of organic matter content would be not active. Therefore, it may need a longer time to observe the effect of rock fragments on organic matter in this area.

Plant roots

Rock fragments are known to decrease plant root growth by reducing soil nutrient capacity and space for root penetration (Estrada-Medina et al., 2013; Rytter, 2012). However, rock fragments can enhance root penetration by providing looser soils at the interface between rock fragments and soil particles (van Wesemael et al., 1995). Moreover, preferential flow paths generated around rock fragments increase spatial nutrient accumulation, which causes a higher root density near rock fragments (Rytter, 2012). In the present study, rock fragments did not have a significant correlation with plant root biomass (Table 7.4). The main reason is likely to be the too small volume of soil samples. Soil samples were collected 20 cm in width and length and 10 cm in depth in each site. In Chapter 3, a higher density of plants roots was observed near rock fragments in the soil deeper than 10 cm (see Figure 3.16). However, in the small and shallow soil sample, plant root biomass is more related to the existence of plant nearby and the rooting habit or root characteristics of the plant.

7.4.3 Eyrewell-specific field condition

In Eyrewell, rock fragments were neither the sole nor the determining factors in in-situ water flow rates (Table 7.3). Also, rock fragments did not have any significant correlation with other soil properties as explained in the previous section. Therefore, the effect of rock fragments on soil water flow in Eyrewell can be illustrated as Figure 7.4, which is a different appearance from a general field condition (Figure 7.3b). Rock fragments were reported to affect soil structure development processes, such as soil compaction, earthworm burrows, soil aggregation, and plant root penetration (Ma & Shao, 2008; Ma et al., 2010). However, soil conversion in this area disturbed the long-term effect of rock fragments on the adjacent soils. As a result, the Eyrewell soil is likely to have the intermediate condition between a laboratory and a natural field. Rock fragments had an independent effect on water flow as a laboratory repacked soil. However, the other soil properties were uncontrolled and had high variability as a natural field soil.

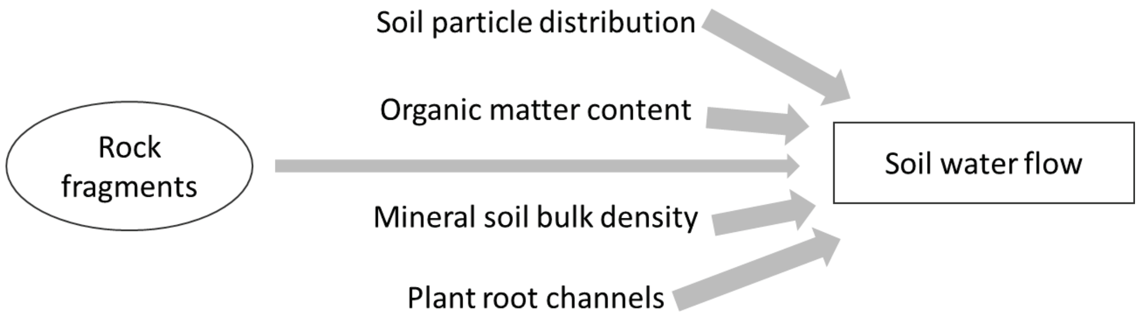

Figure 7.4. Description of the effect of rock fragments on soil water flow in Eyrewll soil. Rock fragments had no influence on the other soil properties and had independent impact on tension infiltration rates.

7.4.4 Tension infiltration rates and preferential flow

Infiltration rates are the reflection of continuous porosity. This indicates that the present study investigated the effect of rock fragments on continuous porosity with different diameter ranges. However, the widest pore range measured in the present study was ≤ 0.1 cm (tension 3 cm), which means pores larger than 0.1 cm were excluded in the present research. Macropores, which is larger than 0.1 cm in diameter (Luxmoore, 1981), is highly associated with rock fragment content and preferential flow. In Chapter 4, it was identified that rock fragments could create pores larger than 0.1 cm along their surface. In addition, in Chapter 3 and 6, rock fragments were demonstrated to have a significant impact on the pattern of preferential flow. This implies the tension infiltration tests in the present study include only limited relationship between rock fragments and soil water flow. Therefore, although rock fragments have little effect on tension infiltration rates, the effect on preferential flow through the pores larger than 0.1 cm would be still validated in the field.

7.5 Conclusion

Ⅰ. Rock fragments had no impact on adjacent soil properties and in-situ tension infiltration rates in the field, even though they have an influence on soil water and nutrient leaching (as shown by the findings of the previous chapters).

Ⅱ. Findings in the field differed to the results of laboratory studies. Unlike laboratory trials, rock fragments were neither sole nor prominent factors for in-situ infiltration rates due to the high spatial variation of a wider range of soil properties.

Ⅲ. A lack of a clear relationship of rock fragments with other soil properties in the field at Te Whenua Hou is probably because the soil profiles were recently constructed and have not developed or stabilized since land conversion.

Ⅳ. The field investigation in the present study did not consider the effect of rock fragments on the creation of the pores larger than 0.1 cm and the patterns of preferential flow, as shown by previous findings in the present study (Chapter 3 and 4). This is a shortcoming of the study presented in this chapter.

Ⅴ. Rock fragments are likely to be a valuable component of Eyrewell soils particularly in the longer term when soils are more developed and stabilized.

Chapter 8

Synopsis and Conclusions

The Eyrewell landscape has recently been converted from a pine forest to dairy pasture and reserves for restoration of native flora and founa. This has been accompanied by major soil disturbance and re-engineering. The Eyrewell soil is known to be drought vulnerable and free-draining because of its high rock fragment content. The present research project investigated the significance played by rock fragments and their physical placement on soil hydrology. The findings have provided a valuable understanding of the effect of rock fragments on soil water flow and solute transport at Te Whenua Hou. The main conclusions of this research are synthesised in the following sections with respect to the five objectives of the study. Then, the contribution of the research and recommendations for future study are presented, prior to closing statement.

8.1 Visualized water flow patterns related to soil characteristics in-situ at Eyrewell (Objective 1)

Land conversion in Eyrewell has undoubtedly created more cracks and resulted in high spatial variance in soil characteristics, which is likely to have increased the occurrence of preferential flow. Preferential flow usually induces a rapid water leaching, so water use efficiency decreases. By visualizing water flow patterns in Eyrewell soil profiles, a significant effect of rock fragments on decreasing rapid water leaching was observed. The main findings were:

- Rock fragments increased water residence time by causing water to detour across the surface of rock fragments.
- Water detouring along rock fragments also resulted in a broader spatial dispersal of water through the soil profile.
- The existence of rock fragments near major preferential flow diversified flow pathways by altering the direction of a part of water and splitting preferential flow. This is also beneficial to a broader dispersal of water.
- Rock fragments increased plant root density in adjacent soils, which probably alters further water flow patterns.

- Some quantity of rock fragments is clearly beneficial through increasing spatial dispersal and retention rates of water.

8.2 Effect of rock fragment content and size on soil hydraulic properties in repacked soil columns (Objective 2)

In repacked soil columns, rock fragments affected water flow rates according to their volumetric content. The main findings were:

- With low rock fragment content (17-20 %), water flow rates were influenced by the size of rock fragments: small rock fragments (2-76 mm in diameter) increased water flow rates while large rock fragments (76-150 mm in diameter) decreased water flow rates.
- With intermediate rock fragment content (20-48 %), the volumetric size of rock fragments had no significant impact on water flow rates. The positive and negative effect of increasing rock fragment content compensated each other, which resulted in no difference in water flow rates.
- At high rock fragment content (40-60%), water flow rates tended to increase with increasing rock fragment content due to increasing less-filled or unfilled voids between rock fragments.
- Water flow rates were lowest at the intermediate range of rock fragment content, particularly at 34 %.
- In terms of restricting water leaching, the optimal range of rock fragment content would be 20-48 % regardless of the size of rock fragments (particularly 34 %) to reduce water flow rates and increase water retention.

8.3 Combined effect of rock fragments and plant roots on nutrient leaching in pot-scale experiments (Objective 3)

Preferential flow increase both water flow rates and nutrient leaching. Rock fragments and plant root channels are the critical factors for preferential flow. However, this study showed that plant roots reduced nutrient leaching in a stony soil. The main findings were:

- No significant effect of rock fragments on plant root biomass was found, which differed to the observation described in Chapter 8.1. Different experimental condition and scale between a pot and a field experiment were the most likely explanation for this.

- Rock fragments on their own increased both the velocity and the total amount of nutrient leaching by decreasing the water and nutrient retention capacity of soils.

- Plant roots on their own decreased the total amount of nutrient leaching by reducing water flow rates and capturing nutrient in the adjacent soils. A higher density of roots had a larger effect on reducing nutrient leaching than through generating preferential flow.

- The positive influence of plant roots on retaining water was more effective than the negative effect of rock fragments. The total amount of nutrient leaching was higher in a non-stony soil without plant roots than a stony soil with plant roots.

- The recorded positive effect of plants was mostly related to the actively growing plant roots, and did not consider dead or decayed root channels. This is discussed in the following section.

- Thus, the existence of living-roots in a stony soil was helpful to reduced nutrient leaching through a stony soil.

8.4 Effects of rock fragment content and decayed plant root channels on solute transport in a lysimeter-scale experiment (Objective 4)

In a lysimeter experiment, solutes were transported by two domains. Firstly, 'Gradual transport' was a solute transport by a uniform water flow through fine pores. Secondly, 'Early transport' was early and rapid solute movement through macropore preferential flow including dead or decayed root channels. The findings were:

- Increasing rock fragment content accelerated solute movement through the Gradual transport by reducing the water and nutrient capacity of soils

- The existence of rock fragments increased the tortuosity of dead or decayed root channels, so soils without rock fragments were disadvantageous due to rapid solute leaching through those channels.

- Soils with 50 % rock fragments were not favourable because of the high velocity and intensive solute leaching through both of the two domains.

- Optimal rock fragment content to reduce nutrient leaching in stony soils was 30 % in terms of slow and low leaching through Early transport and acceptable velocity of Gradual transport.

8.5 Overall effect of rock fragments on other soil properties and in-situ water flow in Eyrewell soil (Objective 5)

The outcomes of this research project suggest the best options for engineered soil profiles of Eyrewell would be to maintain an intermediate amount of rock fragments. From the findings of Chapter 8.2 and 8.4, 30-34 % rock fragments is suitable to increase water and nutrient efficiency of stony soils by increasing their residence time in the soil. In-situ tension infiltration rates were different to laboratory trials in terms of the effects of rock fragments. Rock fragment content was not a determining factor for tension infiltration rates in the field at Te Whenua Hou because of high variation in other soil properties. In addition, the Eyrewell soil was different to a general field soil in that rock fragments had no significant relationship with adjacent soil properties. Land conversion at Eyrewell has probably disturbed the long-term effect of rock fragments on the soil, which had not had sufficient time to become integrated with other components of the soil matrix. Tension infiltration rates could not reflect the effect of rock fragments on preferential flow patterns in the field. Nevertheless, the importance of rock fragments on reducing rapid water and nutrient leaching through preferential flow (see Chapter 8.1, 8.2, and 8.4) would be still effective to some extent in the field. Most of the conversion in Eyrewell from plantation forest to irrigated pasture and restoration plots had taken place by 2018. The present work has shown that more attention to rock fragments in the reconstruction of soil profiles would have been highly beneficial. Although there was some variability, rock fragment content of the Eyrewell soil averaged 40 % at 0-40 cm depth and 60 % at 40-80 cm depth. The findings of the present research project indicate there would be benefits through removal of 6-10 % of rock fragments from 0-40 cm depth and removal of 26-30 % of rock fragments from 40-80 cm depth. If this removal had been done, it would have decreased up to 25 % of water leaching and 21 % of nutrient leaching. In a landscape engineering context, it may be easiest to aim to remove significant quantity of rock fragments from the deeper layers in future land conversions.

8.6 Contribution of this research

Studies on a stony soil around the world have shown conflicting results due to different biophysical, biogeochemical, and other environmental characteristics of research areas. This highlights the need for site-specific research on this topic, and there have been limited efforts to understand stony soils in New Zealand. Furthermore, it has become clear that laboratory trials using repacked stony soils have not corresponded to the results of field investigations. This has constrained the understanding of the role of rock fragments in a soil, and restricted the application of laboratory work to the field. The present research project has contributed to filling this research gap, providing a fundamental understanding of a New Zealand stony soil by synthesising the result from both laboratory and field studies. Te Whenua Hou represents a large-scale landscape conversion of a type has been common in recent years. The results described in this thesis will provide a useful knowledge base for a future research in this area whilst also informing soil engineering practices.

Rock fragments were previously thought to enhance free-drainage of water and nutrients. Removing rock fragments and grading and re-positioning these content and location may present engineering challenges beyond the scope of the present study. The present work has shown that the most efficient method of stony soil management is to maintain an intermediate content of rock fragments to reduce rapid water and nutrient leaching. Increased water and fertilizer efficiency associated with the presence of rock fragments would be economically advantageous by reducing agricultural inputs of waters and fertilizers, whilst also reducing leaching and decreasing environmental concerns. The effect of integration of rock fragments with other soil components in the longer term could have significant and profound effects on water and nutrient movement and management.

8.7 Recommendations for further research

A first recommendation is recommended to investigate the effect of the location of rock fragments in the soil profile on soil hydrology. The present research project has focused on the optimal range of rock fragment content on soil water flow, but other properties of rock fragments also have an impact on soil hydraulic processes. The distribution and alignment of rock fragments in the soil profile are closely related to water flow by affecting continuous porosity. In addition, water hydrology is highly influenced by the position of rock fragments at the soil surface whether they lie on the soil or are embedded partially or completely in the soil.

In agricultural land, the ultimate goal of increasing water and fertiliser efficiency is to sustainably increase or maintain crop productivity. The present research found that rock fragments can increase the efficiency of water and fertiliser in stony soils. Further study on sustainable and optimal application rates of irrigation and fertiliser in stony soils would be highly useful. Furthermore, the present study showed that the effect of rock fragments on aboveground biomass of plants was different depending on plant species (Chapter 5). Further research is recommended to explore how different plant or crop species productivity is affected by rock fragments. Improved selection of plants could be an additional strategy for successful land use of stony areas.

As found in the present research project, soil cracks are one of the main preferential flow pathways at Te Whenua Hou. To understand in-situ hydrological characteristics, soil cracks need to be involved in future studies in this area. More widely, the influence of the existence of rock fragments on generating soil cracks or developing crack networks is not completely understood. Besides other physical effects, rock fragments have been reported to be related to soil temperature which is one of the triggering causes of soil cracks. The presence of rock fragments would have a significant impact on the pattern of soil cracks.

Further research on these topics would be highly valuable to establish an additional knowledge on physical properties of stony soil and soil hydrology.

8.8 Closing remarks

This research project has provided an evaluation and guidance for an optimal prescription for rock fragments in the soils by integrating laboratory trials and field investigations to investigate preferential flow patterns, saturated and unsaturated water flow rates, continuous porosity, and solute transport. The existence of rock fragments is undoubtedly beneficial for efficient soil management in this area, but a question about the longer-term development of soils and their association and integration with biotic component of the soil remains.

Appendix A

Breakthrough curves from a bromide transport experiment in a lysimeter system (objective 4)

All graphs obtained from the experiment in Chapter 6 present in Figure A.1-A.9. Table A.1 provides a simple description of each graph in these Figures.

Table A.1. Explanation of each graph in Figure A.1-A.9.

Graph	Explanation
(a)	Comparison of soil EC peaks with and without bromide (see Chapter 6.2.2). When the peak of ‘bromide’ was higher than ‘only water’, it was judged that bromide had impact on soil EC.
(b)	Comparison of soil VWC with and without bromide (see Chapter 6.2.2). The judgement on soil EC peaks was acceptable only when the increases of VWC were similar at ‘only water’ and ‘bromide’.
(c)	Soil EC changes during 2.5 hours after bromide application.
(d)	Soil VWC changes during 2.5 hours after bromide application.
(e)	Bromide breakthrough curves of leachate (see Chapter 6.2.3).
(f)	Volumes of leachate at each time of collection (see Chapter 6.2.3)

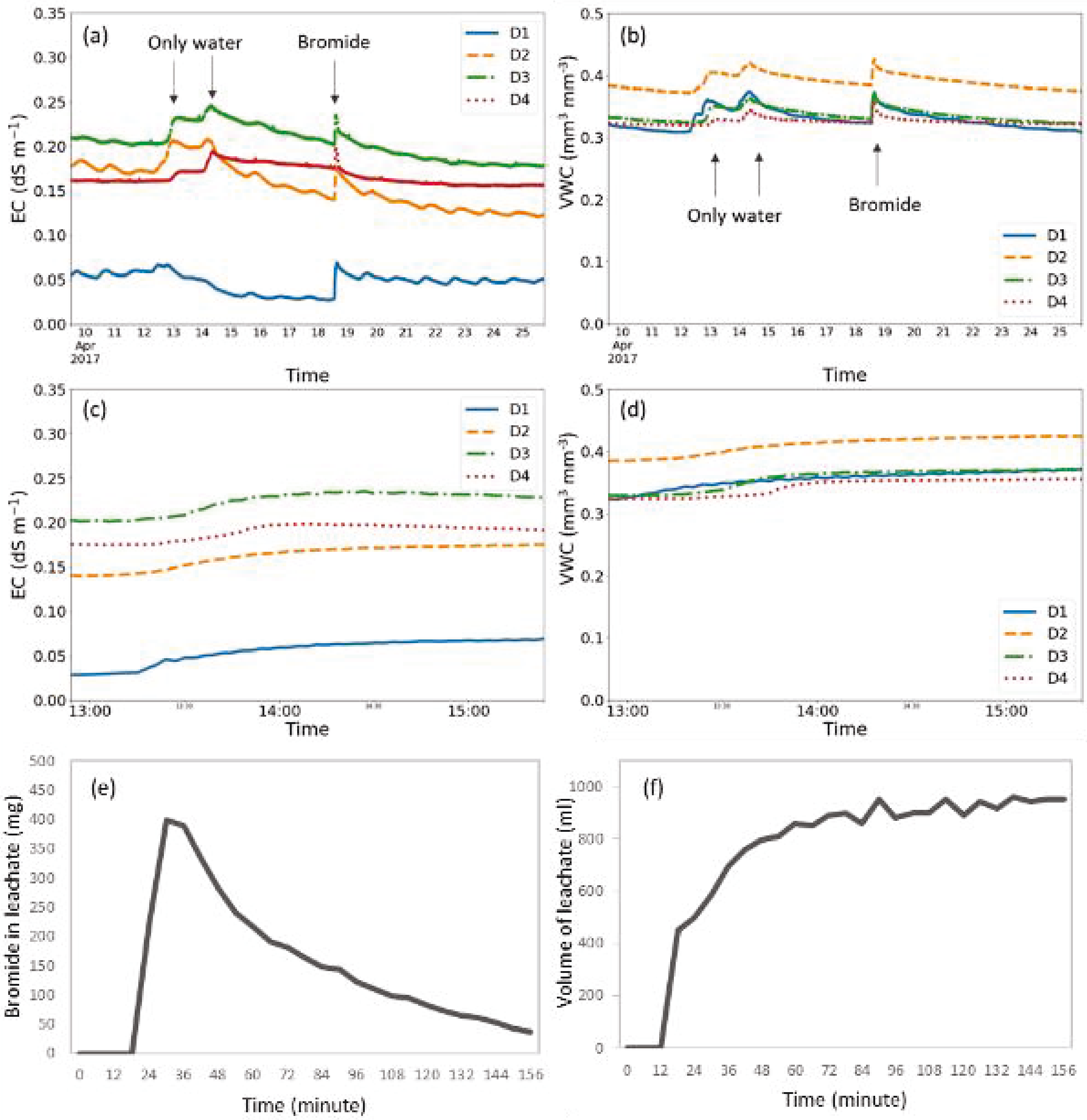

Figure A.1. All graphs obtained from L0-1; (a) comparison of soil EC peaks with and without bromide, (b) comparison of soil VWC with and without bromide, (c) soil EC changes during 2.5 hours, (d) soil VWC changes during 2.5 hours, (e) bromide breakthrough curve of leachate, and (f) the volumes of leachate (see Table A.1. for more detail).

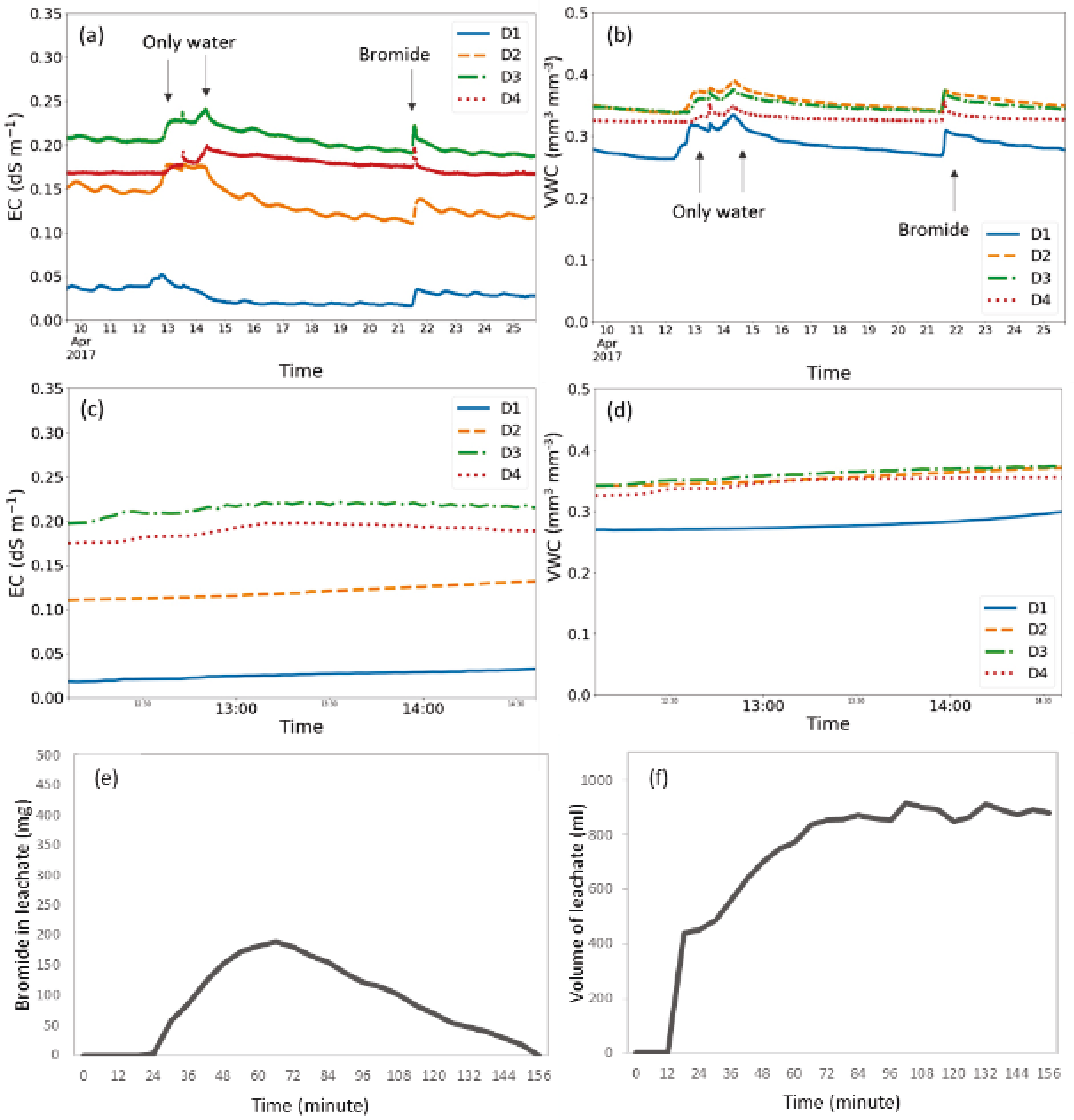

Figure A.2. All graphs obtained from L0-2; (a) comparison of soil EC peaks with and without bromide, (b) comparison of soil VWC with and without bromide, (c) soil EC changes during 2.5 hours, (d) soil VWC changes during 2.5 hours, (e) bromide breakthrough curve of leachate, and (f) the volumes of leachate (see Table A.1. for more detail).

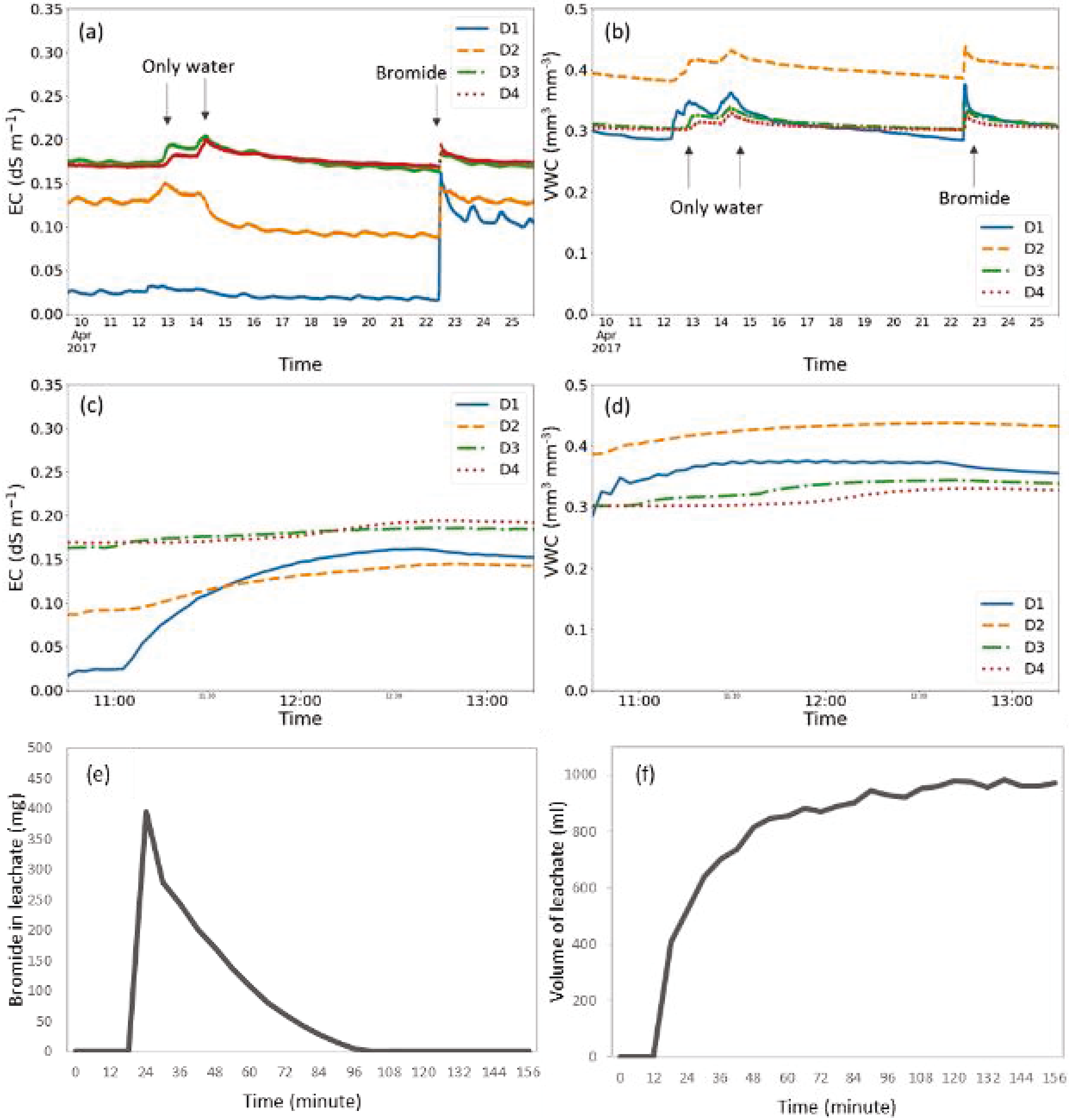

Figure A.3. All graphs obtained from L0-3; (a) comparison of soil EC peaks with and without bromide, (b) comparison of soil VWC with and without bromide, (c) soil EC changes during 2.5 hours, (d) soil VWC changes during 2.5 hours, (e) bromide breakthrough curve of leachate, and (f) the volumes of leachate (see Table A.1. for more detail).

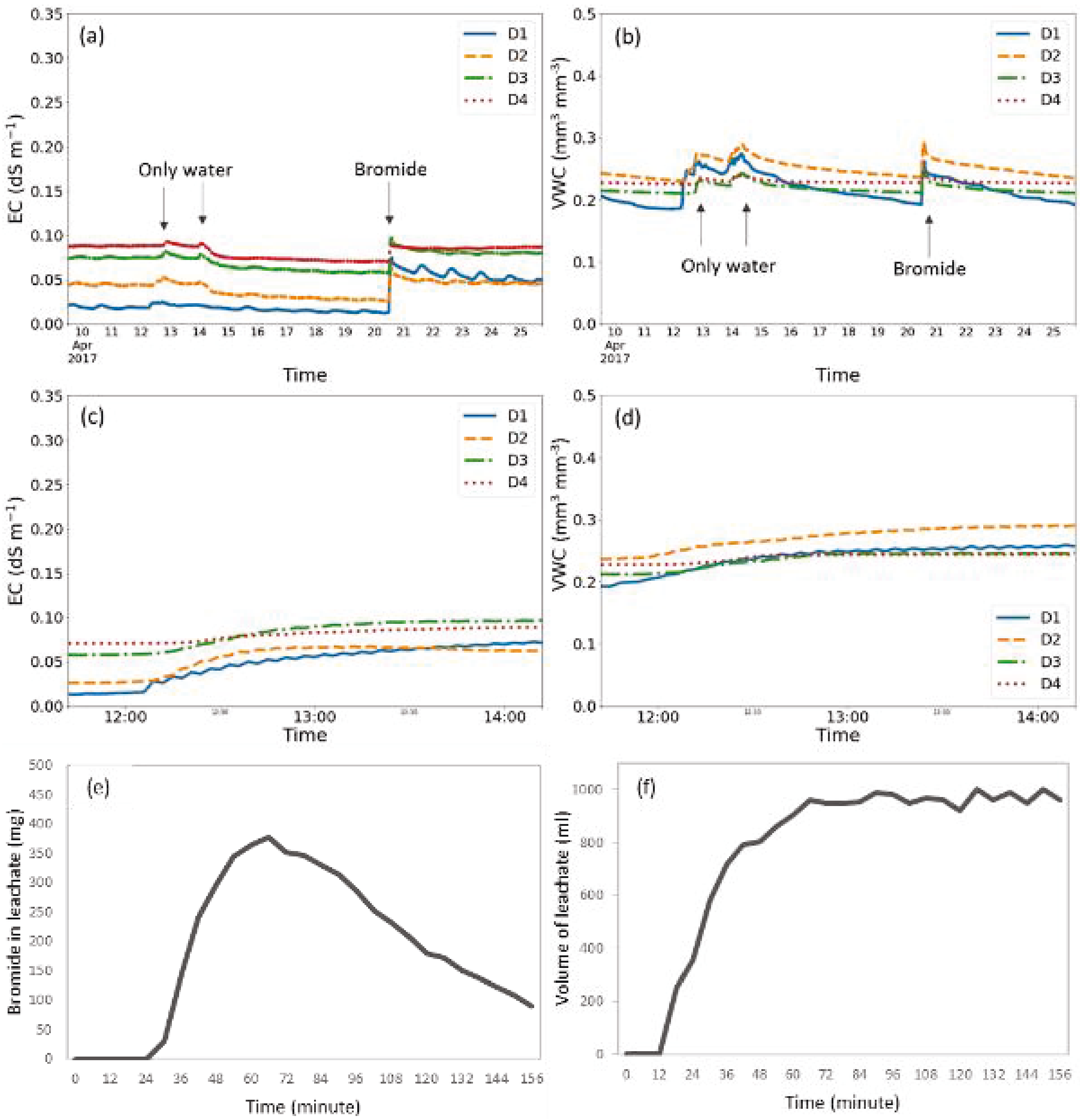

Figure A.4. All graphs obtained from L30-1; (a) comparison of soil EC peaks with and without bromide, (b) comparison of soil VWC with and without bromide, (c) soil EC changes during 2.5 hours, (d) soil VWC changes during 2.5 hours, (e) bromide breakthrough curve of leachate, and (f) the volumes of leachate (see Table A.1. for more detail).

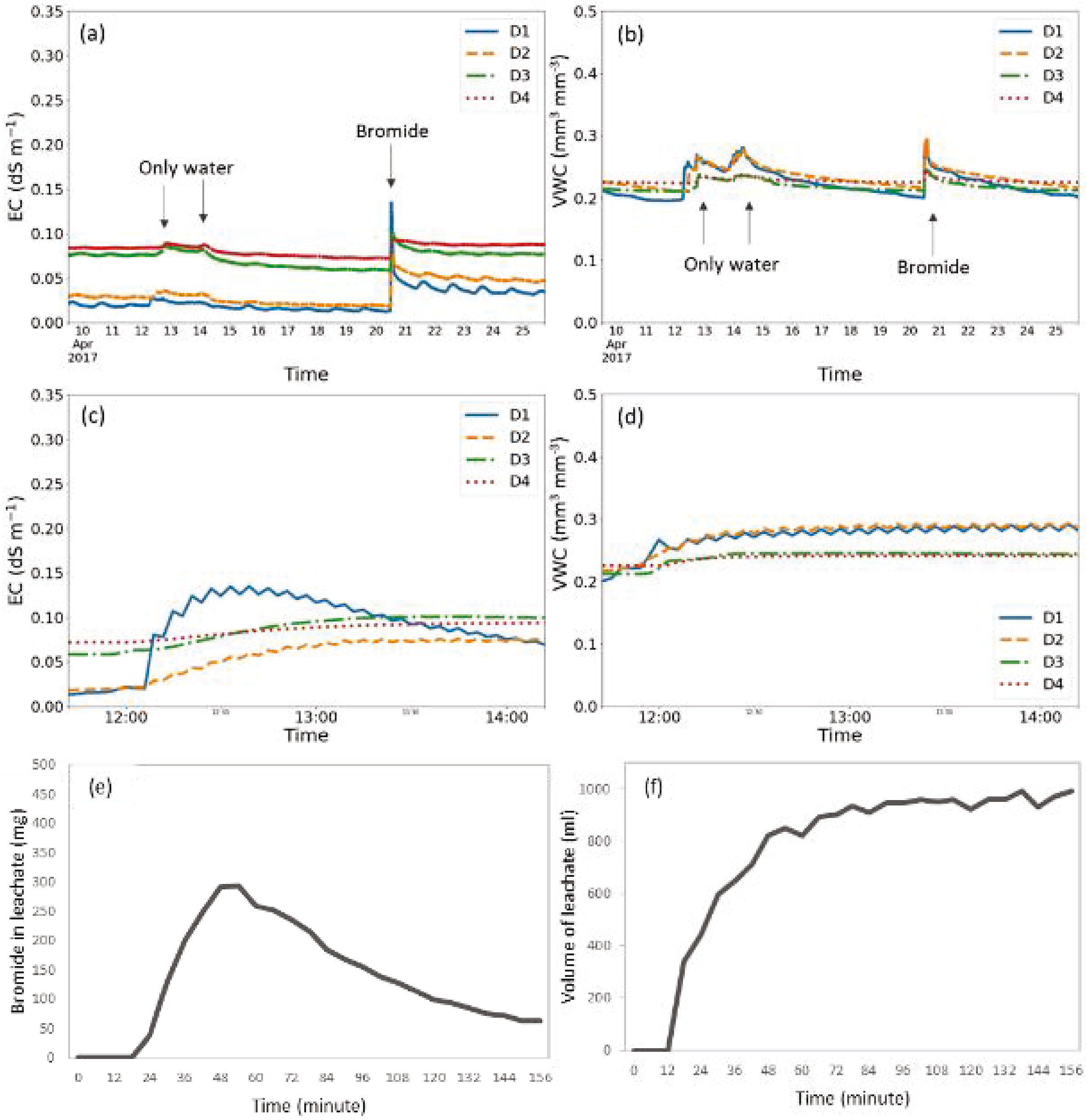

Figure A.5. All graphs obtained from L30-2; (a) comparison of soil EC peaks with and without bromide, (b) comparison of soil VWC with and without bromide, (c) soil EC changes during 2.5 hours, (d) soil VWC changes during 2.5 hours, (e) bromide breakthrough curve of leachate, and (f) the volumes of leachate (see Table A.1. for more detail).

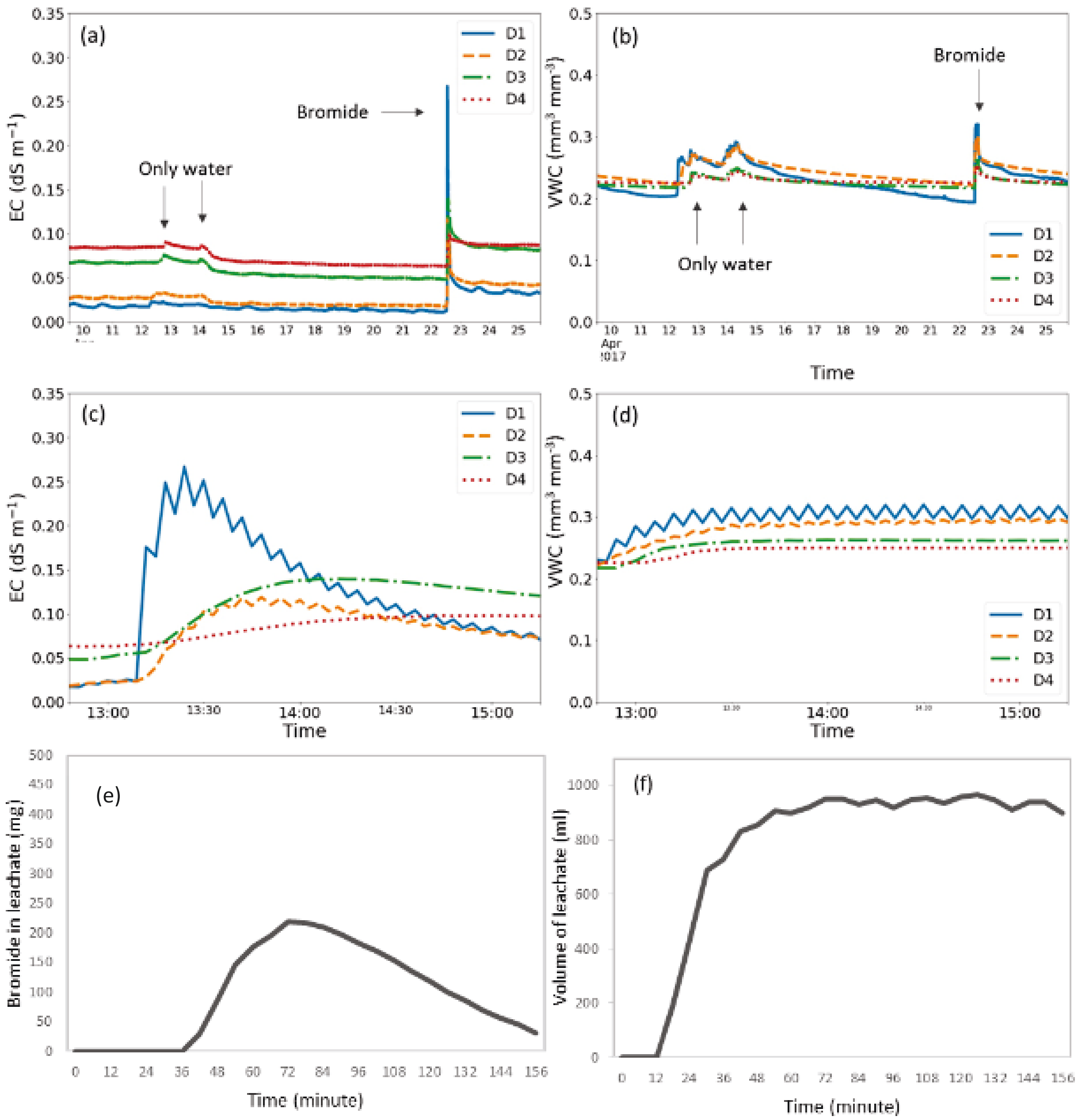

Figure A.6. All graphs obtained from L30-3; (a) comparison of soil EC peaks with and without bromide, (b) comparison of soil VWC with and without bromide, (c) soil EC changes during 2.5 hours, (d) soil VWC changes during 2.5 hours, (e) bromide breakthrough curve of leachate, and (f) the volumes of leachate (see Table A.1. for more detail).

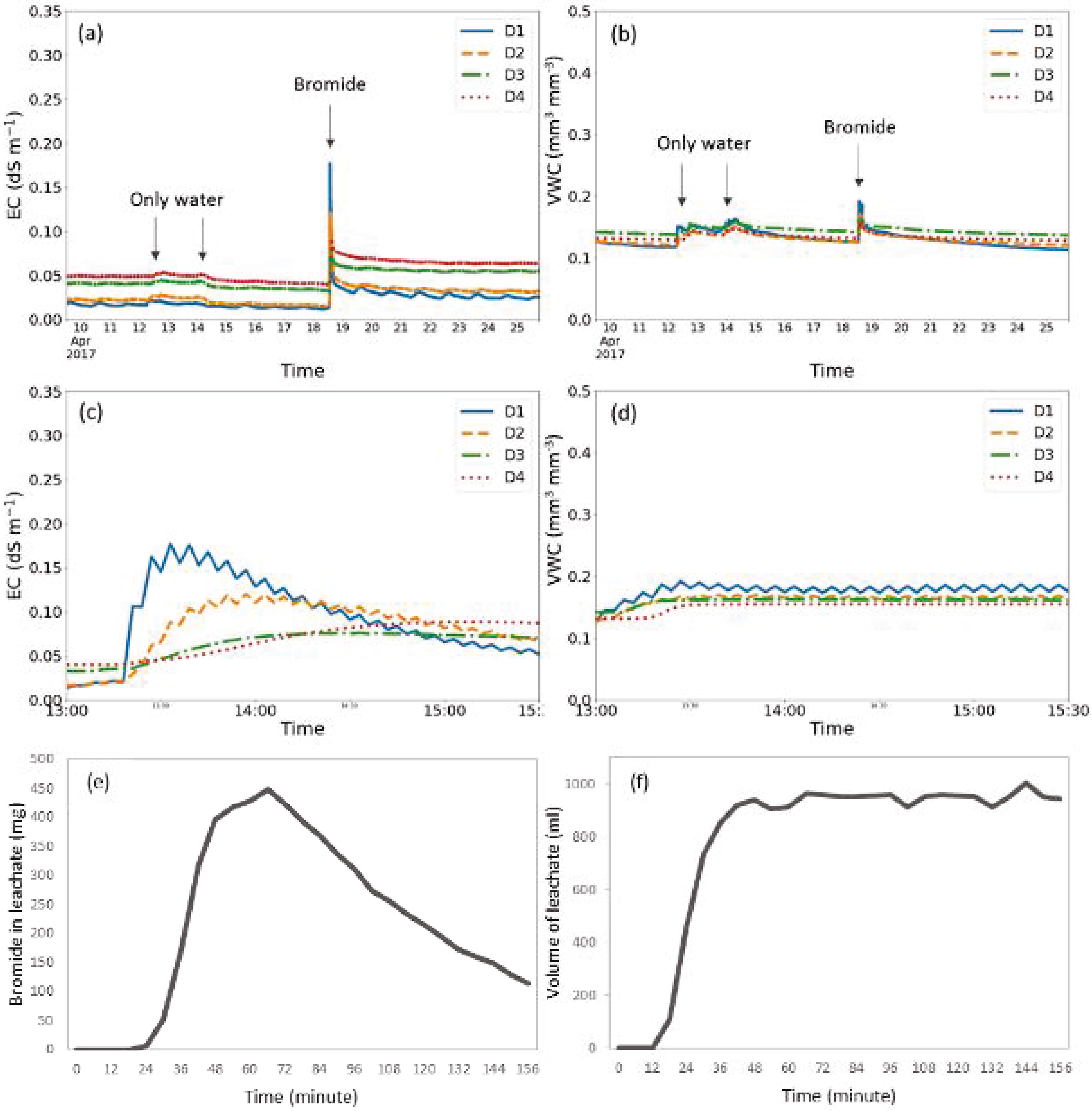

Figure A.7. All graphs obtained from L50-1; (a) comparison of soil EC peaks with and without bromide, (b) comparison of soil VWC with and without bromide, (c) soil EC changes during 2.5 hours, (d) soil VWC changes during 2.5 hours, (e) bromide breakthrough curve of leachate, and (f) the volumes of leachate (see Table A.1. for more detail).

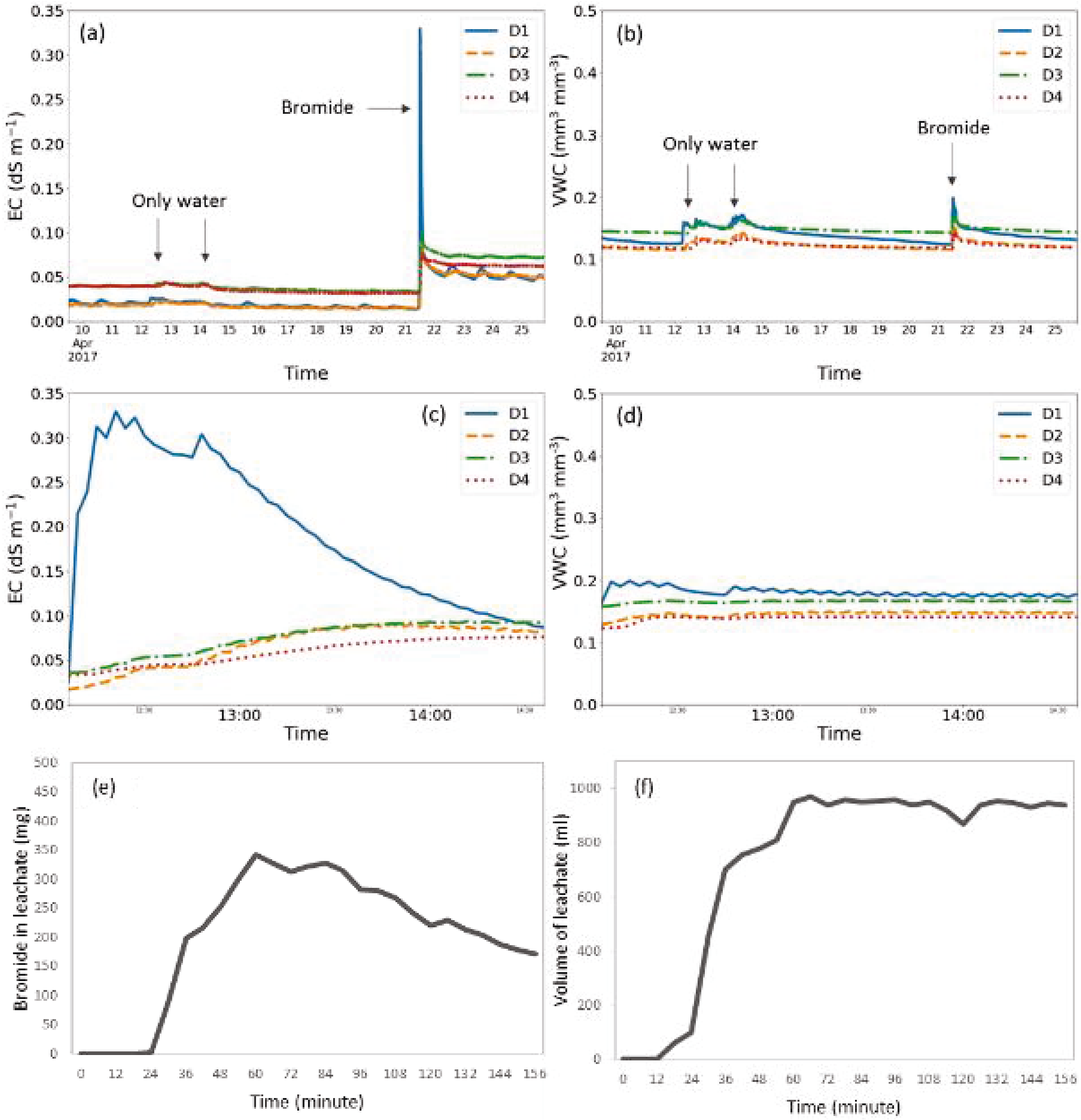

Figure A.8. All graphs obtained from L50-2; (a) comparison of soil EC peaks with and without bromide, (b) comparison of soil VWC with and without bromide, (c) soil EC changes during 2.5 hours, (d) soil VWC changes during 2.5 hours, (e) bromide breakthrough curve of leachate, and (f) the volumes of leachate (see Table A.1. for more detail).

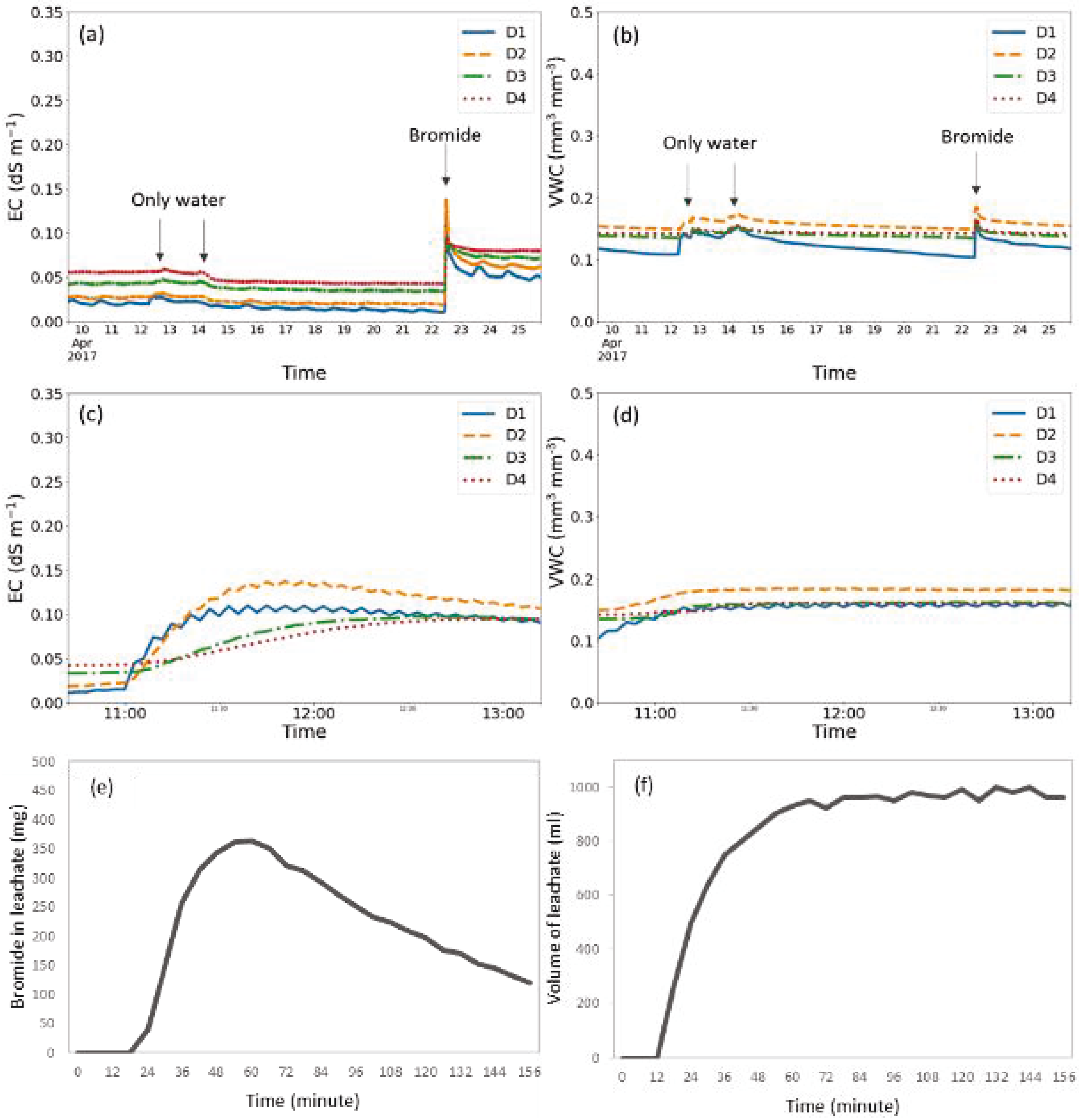

Figure A.9. All graphs obtained from L50-3; (a) comparison of soil EC peaks with and without bromide, (b) comparison of soil VWC with and without bromide, (c) soil EC changes during 2.5 hours, (d) soil VWC changes during 2.5 hours, (e) bromide breakthrough curve of leachate, and (f) the volumes of leachate (see Table A.1. for more detail).

Appendix B

Repellency index of Eyrewell soils (objective 5)

B.1 Procedures for water and ethanol infiltration tests

Water and ethanol infiltration rates were measured in a pine forest near the farm margin (see Figure 3.1). The present study assumed that water repellency of Eyrewell soil was constant at all regions. Vegetation was removed by hand, and a soil surface was flattened. Two tension infiltrometers were filled with water and 80 % ethanol, respectively, and placed on the soil surface (Figure 6.3). A measurement procedure of tension infiltrometers was described in 4.2.7. Four different tensions were applied for each infiltrometers, and each tension of water and ethanol corresponded to the same ranges of pores (Table A.1). The measurement was conducted at six different sites.

Figure B.1. Tension infiltration test with using water and ethanol.

Table B.1. Tensions of water and ethanol, and the corresponding pore diameters.

Related pore diameter (cm)	Tension (cm)	
	Water	Ethanol
≤ 0.023	13	4.9
≤ 0.03	10	3.8
≤ 0.05	6	2.6
≤ 0.1	3	1.3

B.2 Comparison of infiltration rates between water and ethanol

Figure A.2 shows mean values of infiltration rates with water and ethanol under four tensions. Overall, ethanol infiltration rates were higher than water, and the difference became larger with increasing pore sizes. Particularly, water infiltration rates were remained at a low level despite the different tensions. This results demonstrated Eyrewell soils are strongly water-repellent.

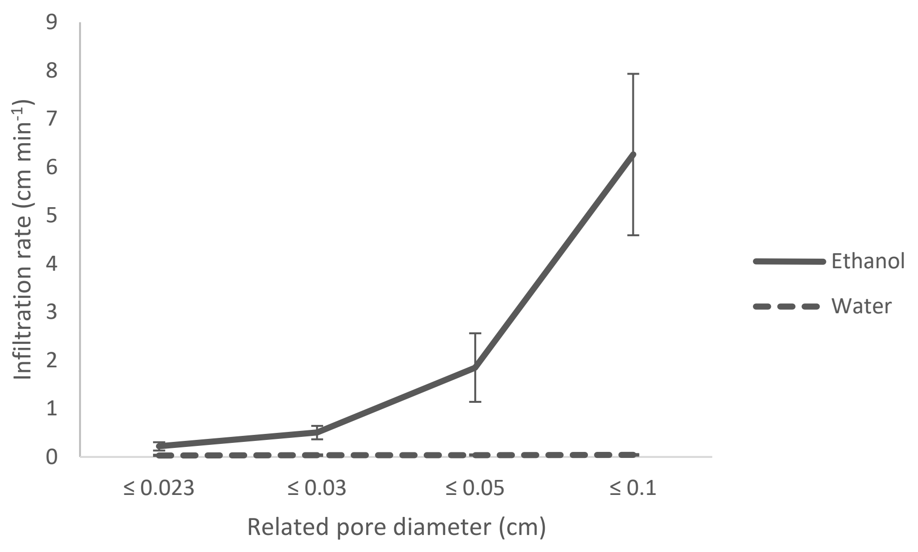

Figure B.2. Comparison of infiltration rates between water and ethanol. Error bars are standard errors.

B.3 Repellency index

To calculate repellent index, sorptivity of water and ethanol were calculated first using a following equation (Philip, 1969).

$$S = \frac{i}{\sqrt{t}}$$

where, S is sorptivity (cm $min^{-1/2}$), i is cumulated infiltration (cm) and t is time (minute).

Repellency index suggested by Tillman et al. (1989) was calculated using a following equation.

$$RI = 1.95\frac{S(e)}{S(w)}$$

where, RI is repellncy index, S (e) is sorptivity of ethanol, and S (w) is sorptivity of water.

Repellency index of each pore diameters were shown in Table A.2. These values were used to calculate potential infiltration rates in Chapter 5.

Table B.2. Sorptivity of water and ethanol, and repellency index for each size of pores.

Related pore diameter (cm)	Sorptivity (ethanol)	Sorptivity (water)	Repellency index	Standard error
≤ 0.023	0.6	0.1	14.5	3.8
≤ 0.03	1.2	0.1	57.0	2.9
≤ 0.05	4.2	0.1	103.6	2.9
≤ 0.1	11.3	0.2	164.5	3.0

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